



HAL
open science

Rejuvenation of ore deposits as exemplified by the Belledonne metalliferous province

Petrus, Johannes Ypma

► **To cite this version:**

Petrus, Johannes Ypma. Rejuvenation of ore deposits as exemplified by the Belledonne metalliferous province. Applied geology. Rijksuniversiteit - Leiden 1963. English. NNT: . tel-01761401

HAL Id: tel-01761401

<https://theses.hal.science/tel-01761401>

Submitted on 9 Apr 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Publications from the Department of Petrology,
Mineralogy and Crystallography of the Univer-
sity of Leyden, Second Series, number.....12.....

With the author's compliments

REJUVENATION OF ORE DEPOSITS
AS EXEMPLIFIED BY THE
BELLEDONNE METALLIFEROUS PROVINCE



P. J. M. YPMA



REJUVENATION OF ORE DEPOSITS
AS EXEMPLIFIED BY THE
BELLEDONNE METALLIFEROUS PROVINCE

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE
WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT
TE LEIDEN, OP GEZAG VAN DE RECTOR MAGNIFICUS
Dr. S. DRESDEN, HOOGLERAAR IN DE FACULTEIT DER
LETTEREN EN WIJSBEGEERTE, PUBLIEK TE VERDEDIGEN
OP DINSDAG 11 JUNI 1963 TE 15 UUR

DOOR

PETRUS JOHANNES MARIA YPMA
GEBOREN TE HEEMSKERK 1930



Vis - Druk - Alphen aan den Rijn

CONTENTS

PART I	METHODS OF INVESTIGATION	page
CHAPTER 1 THE FLUID INCLUSION THERMOMETRY		
1.	Introduction	11
2.	Primary and secondary inclusions	11
3.	Water, as the inclusion's sole constituent	12
4.	Decripitation	12
5.	The presence of a solid phase in the inclusions	15
6.	The presence of two volatile phases in the inclusions	16
7.	Phase relations of the system carbon dioxide-water	16
8.	PX-diagrams of a system of two completely miscible liquids	17
9.	Critical phenomena in a system of completely miscible liquids	18
10.	The PX-diagram of two partially miscible liquids	18
11.	The three-phase line	21
12.	The PX-diagram of two partly miscible liquids at the critical temperature	21
13.	The mutual solubility of carbon dioxide and water at low temperatures	22
14.	The mutual solubility of carbon dioxide and water at high temperatures and pressures	22
15.	Critical phenomena in a system of two incompletely miscible components	25
16.	Retrograde condensation with the system CO ₂ - H ₂ O	25
17.	Infra- and supra-critical gaseous homogenization with CO ₂ -containing fluid inclusions	26
18.	Gaseous and liquid homogenization as a function of the inclusion's composition	27
19.	The temperature-pressure relations at constant volume in one- and two-components system. The VX-diagram.	27
20.	VX-diagrams of a partly miscible two-component system	28
21.	The PV-diagrams for unary and binary systems	33
22.	The rate of pressure increase during the fluid inclusion's homogenization test	33
23.	Decrepitation as a function of pressure increase	37
24.	The failure of the cooling test to produce a third phase with CO ₂ containing inclusions below 31° C. The "corps spherique" of Deicha	37
	Instrumental aspects of the fluid inclusions investigation	38
25.	The gas test and sample selection	38
26.	The heating stage	38
27.	Accuracy of the temperatures measured	39
28.	Preparation of the specimen	39
	Evaluation of the results	39
29.	Mode of representation of the results	39
30.	Transitions between primary and secondary inclusions, and primary inclusion of varying nature	40

31. Summary on the inclusions of the young vein quartz	43
32. Composition of the fluids included in the young vein quartz	43
33. Pressure at crystallization and rate of pressure increase during the homogenization test	45
34. The crystallization temperature	46
35. General crystallization conditions of the young vein quartz	49
36. Inclusions of the old vein quartz	50
37. Composition of fluids included in the old vein quartz	50
38. Homogenization temperatures	51
39. Homogenization pressure, and pressure and temperature at the moment of crystallization of the old vein quartz	51
40. General crystallization conditions of the old vein quartz	52
CHAPTER II X-RAY INVESTIGATIONS	
1. Test for purity of analyzed ankerite samples	55
2. The variation of lattice spacings with chemical composition of ankerites	55
CHAPTER III CHEMICAL ANALYSES	
1. Purpose of the analyses	60
2. The siderite analyses	60
3. Preparation of the sample solution	60
4. Colorimetric analyses of total iron	61
5. Colorimetric analyses of manganese	61
6. Volumetric calcium and magnesium determinations	61
7. Colorimetric determination of titanium	62
8. Acidimetric CO ₂ -determination	63
9. The volumetric ferrous iron determination	64
10. Gravimetric determination of water and correction of carbon dioxide content	64
11. Determination of Ti in hematite, magnetite and ilmenite	64
12. Analyses of sphalerites	65
13. Analyses of galena and tetrahedrite	66
14. Analyses of chlorite and stilpnomelane	66
PART II MINERALOGY	
1. Adularia	67
2. Albite	67
3. Allemontite	67
4. Anatase (Octahedrite)	68
5. Anglesite	68
6. Ankerite	68
7. Annabergite and erythrite	77
8. Antimony	77
9. Aragonite	77
10. Argentite	77
11. Argentopyrite-group	78

12. Arsenic	78
13. Arsenopyrite	78
14. Asbestos	79
15. Azurite	79
16. Barite	79
17. Bismuth	79
18. Bornite	80
19. Bournonite	80
20. Boulangerite	83
21. Calcite	84
22. Cerussite	87
23. Chalcopyrite	87
24. Chlorite	88
25. Cinnabar	89
26. Covellite	90
27. Coronadite	90
28. Dolomite	91
29. Galena	92
30. Gersdorffite	96
31. Goethite	97
32. Gypsum	97
33. Hematite	98
34. Ilmenite	98
35. Lepidocrocite	101
36. Magnetite	101
37. Marcasite	101
38. Millerite	102
39. Niccolite and breithauptite	102
40. Pentlandite	102
41. Polybasite	102
42. Pyrargyrite	105
43. Pyrolusite	105
44. Pyrrhorite	105
45. Quartz	105
46. Safflorite and rammelsbergite	106
47. Siderite	106
48. Silver	113
49. Skutterudite and smaltite	114
50. Sphalerite	114
51. Stilpnomelane	117
52. Tetrahedrite	118
53. Ullmannite	118

PART III THE ORE DEPOSITS

CHAPTER I THE ORE DEPOSITS OF THE VIZILLE REGION

1. Geographical setting and morphology	121
2. Historical notes on the ore deposits	122
3. Mining methods and exploitation data	123
4. Geological outlines	124
5. Structural geology	127
6. Shape and structural features of the ore deposits	128
7. Mineralogy and paragenesis	129
8. References	135

CHAPTER II THE ORE DEPOSITS OF THE ALLEMONT REGION

1. Geographical setting and morphology	137
2. Historical notes	138
3. The mining methods and exploitation data	139
4. Geological outlines	140
5. Structural geology	149
6. The structural features of the ore deposits	150
7. Mineralogy and paragenesis (Allemont)	151
8. References	155

CHAPTER III THE ORE DEPOSITS OF THE ALLEVARD REGION

1. Geographical setting	157
2. Historical notes	157
3. Mining methods and exploitation data	158
4. Geological outlines	159
5. Structural geology	163
6. The mineral spring of Allevard	166
7. Shape and structural features of the ore deposits	169
8. Mineralogy and paragenesis	173
9. References	178

CHAPTER IV THE ORE DEPOSITS OF THE AIGUEBELLE REGION

1. Geographical setting	180
2. Historical notes	180
3. Mining methods and exploitation data	181
4. Geological outlines	183
5. Structural geology	183
6. Structural features of the ore deposits	184
7. Mineralogy and paragenesis	185
8. References	192
Summary and conclusions	193
Résumé	197
Samenvatting	199
Acknowledgements	201
Selected references to Part I and II	202
Selected references to the geology and ore deposits of the Belledonne Range	206
List of ore occurrences	210

A geological map of the Belledonne Range has been inserted in the backflap of the cover

INTRODUCTION

This paper presents a mineralogical, geochemical and fluid inclusion investigation of the ore deposits of the Belledonne metalliferous province. This province forms part of an area of Pb-Zn-Cu mineralization situated in the Outer Zone of the Alps. The mineralized area comprises the Hercynian External Massifs and those parts of the upper Pennine nappes that are designated by Trümpy (1960) as parautochthonous basement.

The most comprehensive study on this mineralization is that by Huttenlocher (1934), who differentiates between metamorphic deposits of the crystalline rocks and their Palaeozoic cover (Goppenstein-type) and non-deformed deposits of the Mesozoic cover of the Alps (Binnental-type). The presence of two types of deposits is a consequence of the bicyclic nature of the Alps, having been subjected to the Hercynian and the Alpine orogeny. The metamorphic deposits are of pre-Triassic age, but have been "tectonized" by the Alpine orogeny, while the underformed deposits have been emplaced during the Alpine orogeny.

In analogy with the metallic mineralization of the foreland, where in the crystalline Hercynian Massifs a direct granite-ore relation has been established, the ore deposits of the parautochthonous External massifs are regarded as products of Hercynian intrusive granites.

The ore deposits of Alpine emplacement, however, are not so obviously correlated with acid igneous rocks, since Mesozoic or Tertiary granites are not known from the Outer Zone of the Western Alps. This inconsistency and the particular mineralogy and chemistry of the Alpine deposits have been explained by Schneiderhöhn (1952, 1953) by assuming a rejuvenation of Hercynian deposits during the Alpine orogeny.

Huttenlocher (1953) largely agrees with the theory of Schneiderhöhn, but stresses the likely hood that apart from rejuvenated deposits, primary ones of Alpine age may also occur, such as pointed out by Andreatta (1953). Schneiderhöhn's theory was strongly supported in recent years, when the isotope ratio's of lead and sulphur of certain lead-zinc deposits of Alpine emplacement (Bleiberg) were shown to have Hercynian "model ages" (Houtermans, 1960). Referring to Bleiberg, anomalous lead isotope compositions were called B-type anomalies. This anomaly appeared to be very common in the Alps (Cahen, 1958).

Having proved the actual existence of rejuvenated deposits, the process of rejuvenation remains to be investigated, yet. As possibilities for such a process a mechanical transport along revived faults has been proposed, the ores moving because of their greater plasticity than the host rock. Another possibility is the re-resolution of pre-existing ore in a hydrothermal solvent or hypogene or mixed hypogene-vadose origin. Ore deposits of such rejuvenated hydrothermal genesis will be very difficult to distinguish from primary ones.

Therefore, an investigation of the physical, chemical and mineralogical characteristics of the rejuvenation process has been the main aim of this study. For such a project the Belledonne represents a most suitable area. It is geologically well known and richly endowed with ore deposits. A rejuvenated origin of these ore deposits has already been proposed by Huttenlocher (1953) as he refers to the whole ore assemblage

as being of Alpine age and by Sarrot-Reynauld (1957), who differentiates between deposits of Hercynian and post-Cretaceous age in the southern part of the Belledonne (la Mure Dôme).

The geology of the Belledonne is typically for that of an External massif of the Alps, both Hercynian and Alpine orogeny have affected it. The main part of the Belledonne consists of crystalline schists, gneisses and granites. It is unconformably overlain by Upper Carboniferous rocks, which may be deeply pinched into the basement. Permian deposits occur in unconformable contact with the Upper Carboniferous demonstrating a second phase of the Hercynian orogeny.

The Alpine orogeny appears from the position of Mesozoic sediments on a thrust plane (Median Syncline), dividing the Belledonne into two parts: the "Rameau Externe" and the "Rameau Interne". In this paper we will refer to these branches as the Outer and Inner Zone. This division is believed to be at least of Hercynian origin, if not older (Tobi, 1959). The overthrust of the Inner Zone over the Outer has caused a gravitational gliding of the formerly autochthonous Mesozoic cover, which now occurs as a range of border hills ("Collines Liasiques"). In the descriptive part of the ore deposits the geological situation will be briefly mentioned as far as it has a bearing on the genesis of the mineralization. For more complete treatises on the geology of the Belledonne the reader is referred to: Gignoux and Moret (1952), den Tex (1950), Bordet (1957), Tobi (1959), Dondey (1960), and Kalsbeek (1962).

PART 1 METHODS OF INVESTIGATION

CHAPTER 1

THE FLUID INCLUSION THERMOMETRY

1 Introduction

Most non-opaque minerals at high magnifications (500 x) show the presence of fluid filled inclusions. Already in 1858 Sorby recognized the mineral genetic implications of these inclusions. He presumed the fluids included to have been involved in the deposition of the host mineral, and the two or three phase state of the inclusions at room temperature to be the result of cooling of a primarily homogeneous fluid, which assumption led him to the very important conclusion, that on heating such inclusions the temperature at which homogenization is achieved might be the minimum temperature of crystallization.

The use of these fluid inclusions as geological thermometers, however, involves more assumptions than listed above. They include apart from the supposed homogeneity of the fluid at the moment of entrapment (which is not always necessarily the case) and the primary character of the inclusions, the absence of leakage and the impossibility of later addition of material. That addition along micro-cleavage planes actually can happen, has been shown by Kennedy (1950a). This may be the case with the high temperature inclusions in marine salt deposits.

2 Primary and secondary inclusions

Not all inclusions in minerals are of primary nature; i.e. have entrapped fluids in cavities occurring along the surfaces of growth of the crystals. Many of them have to be regarded as traces of fluids passing along cleavage planes or fractures in the already crystallized material. These are called secondary inclusions.

The only means of distinguishing between both are given by the mode of emplacement, neither shape nor content provide any information. Therefore, the normal thin sections with their almost two dimensional aspect are not so appropriate for inclusion study as mounted grains, such as recommended by Deicha (1955).

Marks that may help to discriminate between primary and secondary inclusions are listed by Laemmlein (1929), Cameron (1953) and Deicha (1955), and may briefly be summarized as solitary or crystallographically induced positions for the primary inclusions, and as an arrangement in intersecting or branching rows or planes, even cross-cutting the crystal boundaries, for the secondary ones.

3 Water, as the inclusion's sole constituent

Generally water is the main constituent of the inclusion's content, and all theoretical considerations reflecting upon the behaviour of the inclusions on heating are based on the phase relations of water.

The phase relations are determined by three variables: temperature, pressure and volume. Although the system water-water vapour is perfectly defined by pressure and temperature alone, still the volume is drawn into consideration, since it determines the PT-interval in which the two-phase state can exist. If we compare, for instance, the effect of heating a closed system filled at 20° C for 5/6 part with water, with another closed system filled for only 1/6 part with water, we will notice the first system to show a liquid expanding till homogenization into a liquid phase is achieved, whereas the second one on heating will show boiling of the liquid followed by homogenization into the vapour phase.

The block diagram shows the P-T-V relations (fig. 1). The thick black line (two-phase line) encloses the area of equilibrium between vapour and liquid phases. This area is a cylindrical surface parallel to the V-axis.

A section of this diagram at constant temperature shows, that a reduction of volume will cause the pressure to rise until the moment that condensation starts, during which process the pressure remains constant, the system being uni-variant (fig. 2).

When the vapour phase has vanished, further volume reduction will result into a sharp rise of pressure, the compressibility of a liquid being very small as compared with that of vapour.

At higher temperatures, once homogeneity in the liquid phase is achieved, the pressure rise becomes less pronounced, since the compressibility of vapour and liquid tends to become equal towards the critical point.

The PT section of the diagram at constant V (fig. 3) is also of interest for an understanding of the behaviour of the inclusion-filling, since the pressure increase on heating appears to occur independently of the vapour-liquid ratio during the interval that two phases are present. The pressure increase on heating the system beyond the two-phase boundary-curves varies greatly, and depends wholly on the relative amounts of vapour and liquid at room temperature.

4 Decrepitation

The increment of pressure may result in a decrepitation of the inclusions. Such decrepitation may appear under the microscope as an explosive escapement of the inclusion's content in the gaseous state.

The large volume occupied by vapours at elevated temperature (200° - 350°) and atmospheric pressure as compared with the small volume of the inclusion's content in the liquid state enables decrepitation to be made visible in an oil-filled test tube without the aid of a microscope. When decrepitation occurs, bubbles are seen to emerge from the heated sample (Decrepitoscopy - Deicha, 1955).

Scott (1948) and Smith (1949) have developed a technique for

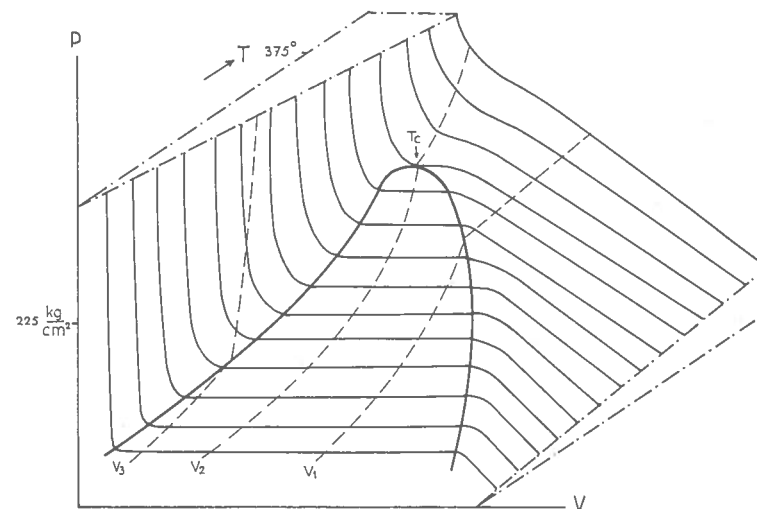


Fig. 1. Pressure-temperature-volume relations of water.

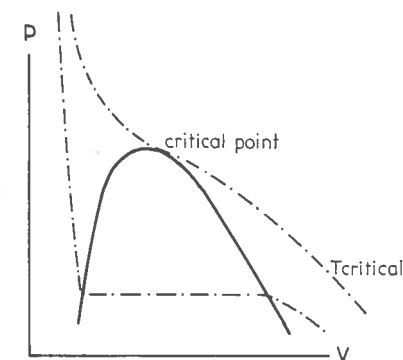


Fig. 2. Pressure-volume relations of a unary system.

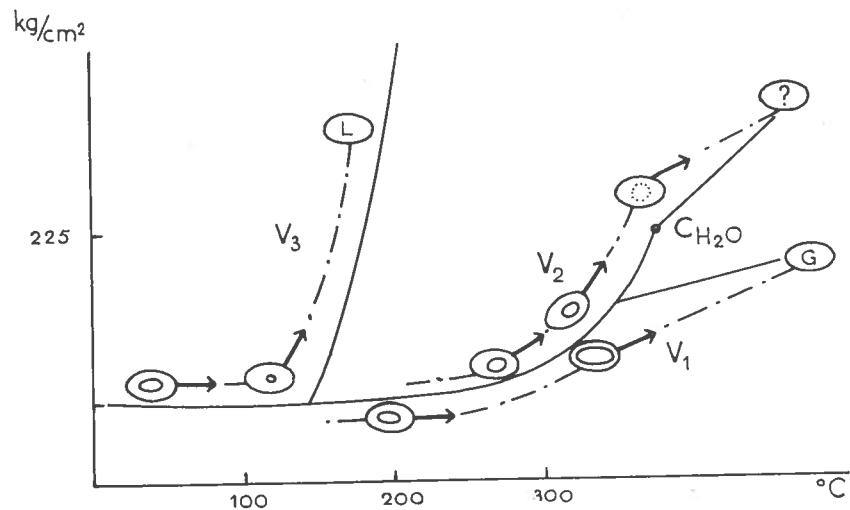


Fig. 3. Pressure increase on heating inclusions of different filling degrees, corresponding with V_1 , V_2 and V_3 of figure 1.

recording decrepitation by amplifying its crackling sounds to a registrable level.

Both methods are used as substitutes for the rather tedious technique of determining homogenization temperatures by means of the microscope heating stage. Decrepitation methods, however, can not discriminate between primary and secondary inclusions, nor can they distinguish liquid from gaseous homogenization. Moreover the resolving power of decrepitation-thermometry quickly diminishes with lower filling degrees at room temperature.

Only at relatively low temperatures of homogenization (250°C) in the liquid phase the pressure increase on heating is sharp enough to be predominant over other factors controlling decrepitation, such that both decrepitation and homogenization temperatures may be assumed to be comparable.

Among the other factors controlling decrepitation the mechanical strength of the host mineral and the degree of cleavage are commonly mentioned. Readily cleavable minerals are not appropriate for fluid inclusion study on the heating stage of the microscope. The pressure exerted by the expanding fluids will crack the mineral possibly long before homogenization is achieved. Thus, mainly the inclusions of minerals with poor cleavages such as quartz, beryl and apatite have been subject of study.

Many microscopic observations on decrepitation and homogenization have led the author to attribute an important role also to the shape, size and position of the inclusions, in controlling decrepitation. It is readily conceivable that heating of inclusions situated in one plane, will cause an inhomogeneous pressure field to build up, which may result in fracturing of the host mineral along this plane. Large flat, or anastomotic inclusions will cause the same phenomenon. These inclusions generally do not persist until homogenization of the content is achieved. Equidimensional inclusions of rounded shape, on the contrary may be left unimpaired by decrepitation, even when heated above their homogenization temperature.

5 The presence of a solid phase in the inclusions

Considering the behaviour of the inclusion's content on heating from the view point of the phase relations of water alone, means a deceiving simplification. Tiny cubic crystals inside the inclusions, or a more or less opaque coating of its walls indicate that the presence of solid phases of varying solubilities have to be regarded.

Soluble matter will effect a prolonged two-phases line as a result of the increase of temperature and pressure of the critical point. It will be difficult, however, to perform complete homogenization with inclusions containing a solid phase. This is due to the limited time of experiment (par. 27) as compared with the rate of solubility on increase of temperature. Even the cubic isotopic crystals, the composition of which is assumed to consist of alkali-chlorides *) fail to

*) All analyses of fluid inclusion contents available show the presence of K, Na or Ca-chlorides.

become completely dissolved after homogenization of the fluid contents has been achieved, notwithstanding the steep increase of solubility of such salts (NaCl-excepted) with temperature.

Hence, we may expect that it will be quite impossible to produce homogenization of inclusions containing slightly soluble matter such as SiO_2 in the case of quartz as host mineral. The effects, however, of compounds of low solubility, on the phase relations of the solvent (water), are negligible, because of the very small quantities involved. The solubility of SiO_2 in water at 4000°C and 2000 kg/cm^2 does not amount to more than 2 mol. % (Khitarov, 1956a) even in the presence of alkaline matter or bicarbonates.

6 The presence of two volatile phases in the inclusions

Much more pronounced are the effects in the case of the presence of compounds of a critical point of a lower temperature than that of water, viz. compounds that are liquid or gaseous at room temperature and atmospheric pressure. Such a compound, commonly present in inclusions, is carbon dioxide.

Many studies dealing with fluid inclusions in quartz and beryl record the appearance of a second liquid phase when the inclusions are cooled below 31°C , the critical temperature of carbon dioxide. The nature of this second component can also be ascertained by chemical methods, for instance by the reaction with barium hydroxide.

Deicha (1955) has emphasized the virtual omnipresence of carbon dioxide in liquid inclusions. He pointed out, that even in those cases where cooling below the critical temperature of carbon dioxide fails to produce a second liquid phase, carbon dioxide, actually, may be present in the vapour phase. In order to discriminate between inclusions with a vapour phase apparently consisting of water vapour alone, and vapour phases containing carbon dioxide, he called the bubbles of the first type "vide de retraite" - void of shrinkage, and the second type "corps spherique" - spherical body.

He developed a simple technique for detecting compounds normally occurring in the gaseous phase at atmospheric pressure and pressure, provided they are present under pressure in the inclusions.

His technique consists of crushing the mineral to be investigated immersed in oil between two slides of glass under the microscope. The act of crushing releases numerous minute gas bubbles, which unite quickly into observable quantities. Considering the size of the mineral grain and the size and relative number of inclusions, experience will give an idea of the relative amounts of gas released.

For the proper understanding of the behaviour of the CO_2 -containing aqueous inclusions on heating or cooling, a brief theoretical treatise on the phase relations of the system $\text{H}_2\text{O}-\text{CO}_2$ will be given. The presence of dissolved solid matter will be left beyond consideration.

7 Phase relations of the system carbon dioxide-water

All authors dealing with CO_2 -containing liquid inclusions have

been able to perform a homogenization of the content on heating such inclusions. Some record a homogenization in the gaseous phase (Smith, 1959; Cameron, 1953; Yermakov, 1957), but generally homogenization into a liquid phase takes place. Cameron et al. (1953) have also noted a sudden transition of the two-phase state into the one-phase state.

These observations indicate that CO_2 at least at high temperatures (recorded homogenization range: $280^\circ - 390^\circ$), is completely soluble in water. The appearance of a second liquid phase at temperatures below 31°C gives evidence of only partial miscibility of water and liquid carbon dioxide at low temperatures.

For considering the composition of both liquid phases and the vapour phase, and the pressure and temperature intervals in which three or two phases co-exist, we will first describe the phase relations in the case of two completely miscible liquids.

8 PX-diagrams of a system of two completely miscible liquids

The composition of the vapour and liquid phase is most conveniently represented by a PX-diagram. This is a section at given temperature of the three dimensional pressure - composition - temperature diagram (fig. 4).

If the vapour pressure of the pure components are P_A and P_B , a liquid of composition X will have a vapour pressure somewhere between P_A and P_B , the value of which may be calculated according to Raoult's law, from the partial pressures and the molecular proportions.

The partial pressures of the components, however, are not linear functions of the molecular percentages, owing to the feature that the van der Waals forces of attraction between one kind of molecules generally are not equal to those between the other components. In case the van der Waals forces between molecules of the same kind are stronger than from one to another, the total vapour pressure will be higher than calculated from Raoult's law. The total vapour pressure may even be higher than P_A and P_B , provided that P_A and P_B do not differ much (fig. 4a). Conversely, if the mutual attraction between A and B is stronger than between A and A or B and B, the total vapour pressure may become less than P_A and P_B each, if the values of P_A and P_B are sufficiently close (fig. 4b).

The different forces of attraction that result into the deviation from Raoult's law will, as a consequence, also cause the composition of the vapour phase to be different from that of the liquid phase.

In which sense the difference will occur as compared with the composition of the liquid phase, is stated by the rule of Konowalov, viz: that the vapour will contain more of that component the addition of which to the system will raise the total pressure, or excluding maximum or minimum total pressure curves: the vapour phase contains more of the component with the highest vapour pressure than the liquid phase does.

The changes in composition with pressure are given by the vapour composition curve. Hence, when raising the pressure of a gaseous mixture of composition X_n condensation will start, according to the diagram, at the pressure P_n with the formation

of a liquid of composition B_n (fig. 4).

The diagram also provides information about the quantities of liquid produced during the condensation process, since the quantities of both phases are inversely proportional to the length of the portions of the tie-lines connecting points of equilibrium between both phases, divided by the pressure line.

9 Critical phenomena in a system of completely miscible liquids

With changing temperatures the position or shape of the curves in the PX diagram will alter, but the general picture will remain the same, until the critical temperature of one of the components has been reached. At this temperature continuity occurs between vapour and liquid phases and hence one of the ordinates is no longer divided into two parts denoting liquid- or vapour-phase stability of the pure component. Both vapour composition and vapour pressure curves will separate from the ordinate to form a loop-shaped termination. On raising the temperature the curves will contract till they disappear into the critical point of the less volatile component (fig. 5).

On the critical termination of the curves, we will distinguish between three points of interest: P_m a point of maximum pressure at which vapour and liquid can still co-exist; X_m , the extreme value of composition at which both vapour and liquid can be present; and the critical point, C, at which continuity between vapour and liquid phase is achieved.

The PX diagrams are not very suitable for representing the change of position of the critical points with varying P, T and X values, since the curve connecting the critical points, the so called critical curve of the first order, is a line tangential to the three dimensional PTX figure (or boundary surface) in such a position as a cylinder with its axis parallel to X touches the figure rolling it over.

The critical curve is more clearly represented using PT sections at a fixed composition. A series of such PT-sections is displayed in figure 6. The tangent line to these PT-curves is the projection on PT of the critical curve (Caubet, 1902). The second order critical curve is a line developed by the tangent points of a cylinder rotating parallel to the P-axis.

Returning to the PX-diagram (fig. 7), it can be seen that releasing isothermally the pressure of a supracritical mixture of a composition between C and X_m , condensation of a liquid will start, which will first increase in quantity and later disappear completely. The condensation on releasing pressure is a feature contrary to the common phenomena of evaporation. It has been called "retrograde condensation" by Kuenen (1893). Since, this phenomenon has drawn little attention till it was almost re-discovered by petroleum-chemists in the thirties for explaining the condensation of a clear oily matter on pressure release of natural gas (Katz, et al. 1940). The interest of retrograde condensation with regard to the behaviour of the system $CO_2 - H_2O$ will be discussed below.

10 The PX-diagram of two partially miscible liquids

Actually, we may not compare the system $CO_2 - H_2O$ with a common

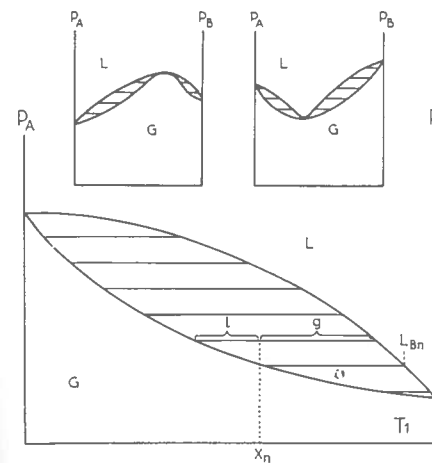


Fig. 4. Vapour pressure and vapour composition curves of a completely miscible binary system; the left inset indicates the course of the curves in case of maximum vapour pressure, the right one refers to the case of minimum vapour pressure.

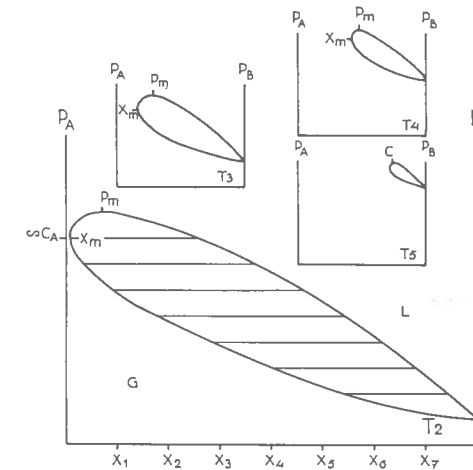


Fig. 5. Pressure-composition diagram of a binary system heated above the critical temperature of its most volatile component.

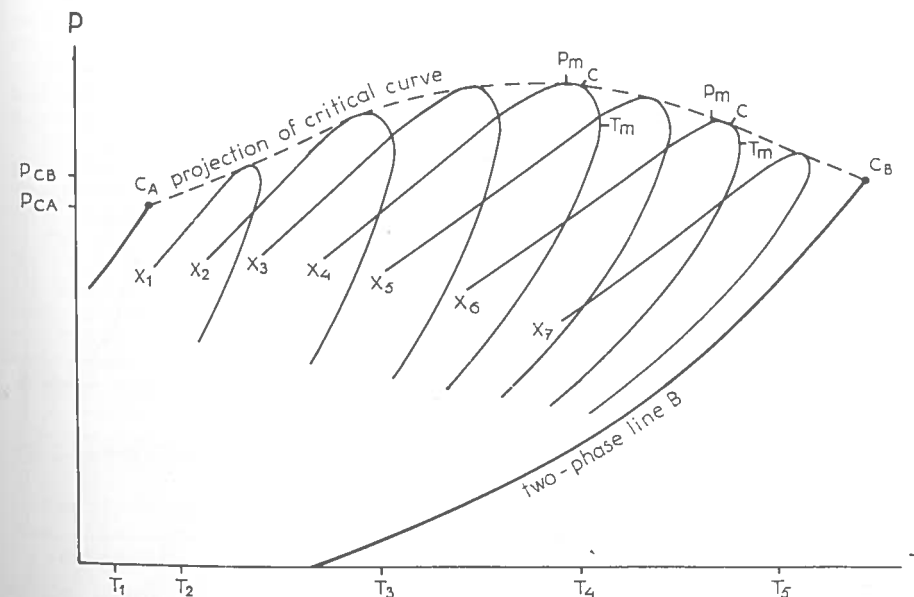


Fig. 6. Projection of the critical curve on the PT-plane, constructed as tangent line to PT-curves of different composition, corresponding to those of figure 5.

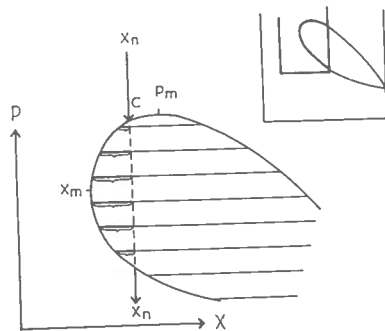


Fig. 7. Detail of a PX-diagram. Demonstrates critical phenomena, such as retrograde condensation.

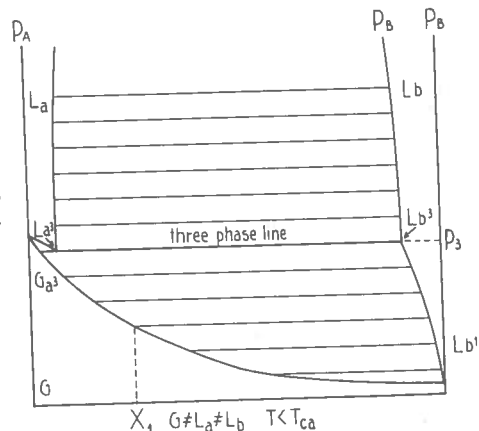


Fig. 8. PX-diagram of two partly miscible liquids at a temperature lower than the critical temperature (T_{ca}) of the most volatile component (P_A).

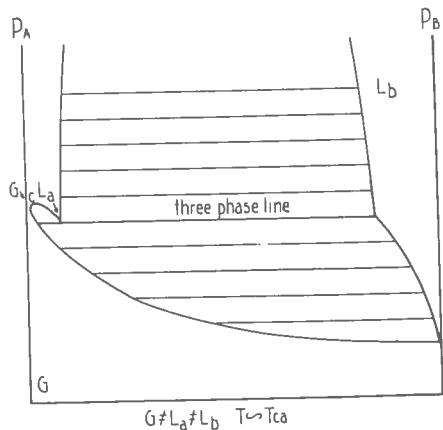


Fig. 9. PX-diagram of two partly miscible liquids at the critical temperature of component A.

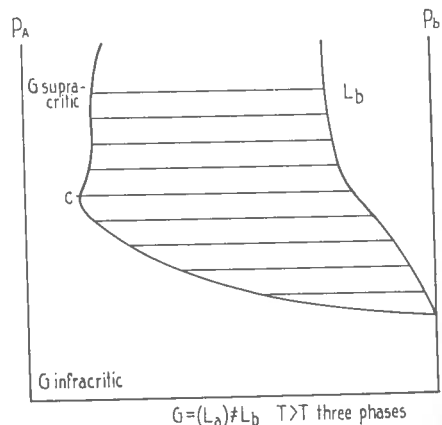


Fig. 10. PX-diagram of a partly miscible binary system at a temperature slightly higher than the three-phase temperature.

binary system, since the liquid phases of both components are only slightly miscible. The aspect of the PX-diagram of such a partly miscible system is represented in figure 8.

The temperature is assumed to be under the critical temperature of the most volatile component. Besides, the composition of the vapour phase is assumed to be situated beyond the compositional range of the liquid phases in equilibrium with it. A condition that occurs with the system $\text{CO}_2 - \text{H}_2\text{O}$ (Kuenen and Robson, 1899) and in general way with all systems having widely diverging vapour pressures.

A gaseous mixture of composition X_1 will start to condense into liquid of composition B_1 on reaching the vapour composition-curve, also called the condensation curve. On continued pressure increase the condensation process will go on forming liquid of gradually varying composition, the vapour composition will move in the same sense (third rule of Konowalov) till the pressure reaches the value of P_3 , the three-phase pressure.

11 The three-phase line

At the three-phase pressure a second liquid will start to condense: the system becomes of three phases, and hence, univariant. This means that at a fixed temperature the pressure will not increase until one phase has disappeared, or conversely, if the volume is kept constant, an increase of temperature will result into a rise of pressure along a certain curve, the three-phase curve. The projection of these lines on the PT plane forms the three-phase curve.

The three-phase curve is comparable with the vapour pressure curve of an unary system and also has a critical end point. Where this point is situated in the PT diagram depends on which homogenization phenomenon occurs first: either the liquids become completely miscible, or one liquid and the vapour phase have a critical transition point.

In the case of the system $\text{CO}_2 - \text{H}_2\text{O}$ the fluid inclusions provide no indication for an increase in miscibility with higher temperature, but at temperatures of 31°C or higher they show the liquid CO_2 phase to become identical with the vapour phase.

The critical temperature and pressure of pure CO_2 amount to 31°C and $71,6 \text{ kg/cm}^2$. Because of the slight solubility of water in liquid CO_2 (Wiebe and Gaddy, 1939) the value of the critical end point of the three-phase line will be very close to the critical values of pure CO_2 . Actually the position of the critical end point will be at a slightly lower pressure but higher temperature due to dissolved water.

12 The PX-diagram of two partly miscible liquids at the critical temperature

Considering the diagram at the critical temperature of CO_2 we see, that as with the first example of two completely miscible liquids, the vapour composition and the total vapour pressure curves, separate from the P-axis, forming a loop-shaped termination (fig. 9). This loop, enclosing the field of co-existing second liquid and vapour phases will contract on

increase of temperature till it disappears in a point on the boundary curve. Through this point also passes the ultimate three-phase line (fig. 10).

With higher temperature than the ultimate three-phase temperature the system becomes bivariant again, the phase difference between the CO₂-rich liquid and vapour having disappeared.

13 The mutual solubility of carbon dioxide and water at low temperatures

In the supracritical state we may compare this diagram with those obtained from completely miscible liquids, heated above the critical temperature of one of the components. They are essentially the same, provided that at higher pressure the miscibility increases.

In the case of CO₂ - H₂O this assumption certainly holds for temperature higher than 280° C, since the miscibility at this temperature is actually observed in the inclusions. As far as is known to the author, no homogenization of inclusions containing water and substantial amounts of carbon dioxide have been recorded at temperatures below 250° C.

Apparently the pressure effect on the mutual solubility of carbon dioxide and water is so slight between 31° and 250° C that within the experimental range (up to 1000 kg/cm²) no homogenization can be expected. The investigation of Sander (1912) also points in this direction. He observed in the low temperature range (20° - 35° C) a marked deviation from Henry's law, and a partial validity of this law for the 1000° C isotherm at relatively low pressures (up to 170 kg/cm²).

Wiebe and Gaddy (1939), however, whose experiments were performed at still higher pressures (up to 700 kg/cm²) concluded to the same deviation of Henry's law, the solubility of carbon dioxide in water being smaller than should correspond with the pressure. This deviation is easily explained since, according to the data of Kennedy (1954), carbon dioxide attains the density of a liquid at the temperatures and pressures at which proportionality between increase of pressure and solubility ceases to be a linear function, (being 0,65 g/cm³ at 31° C and 75 kg/cm². Pressure has only slight influence on the mutual solubility of two liquids.

14 The mutual solubility of carbon dioxide and water at high temperatures and pressures

The most complete treatise on the solubility of CO₂ in water at high temperatures and pressures we owe to Khitarov (1958) and Malinin (1959). They have investigated the system at temperatures between 200° and 330° C and pressures from 100 to 500 kg/cm². Their data enable the construction of the 200°, 250°, 300° and 330° C isotherms (fig. 11).

The trend of the 300° C isotherm is such that at a pressure of about 600 kg/cm² the curve is expected to have a critical end point (fig. 11). The maximum pressure of the 330° C isotherm is situated within the very pressure range of the experiments (at

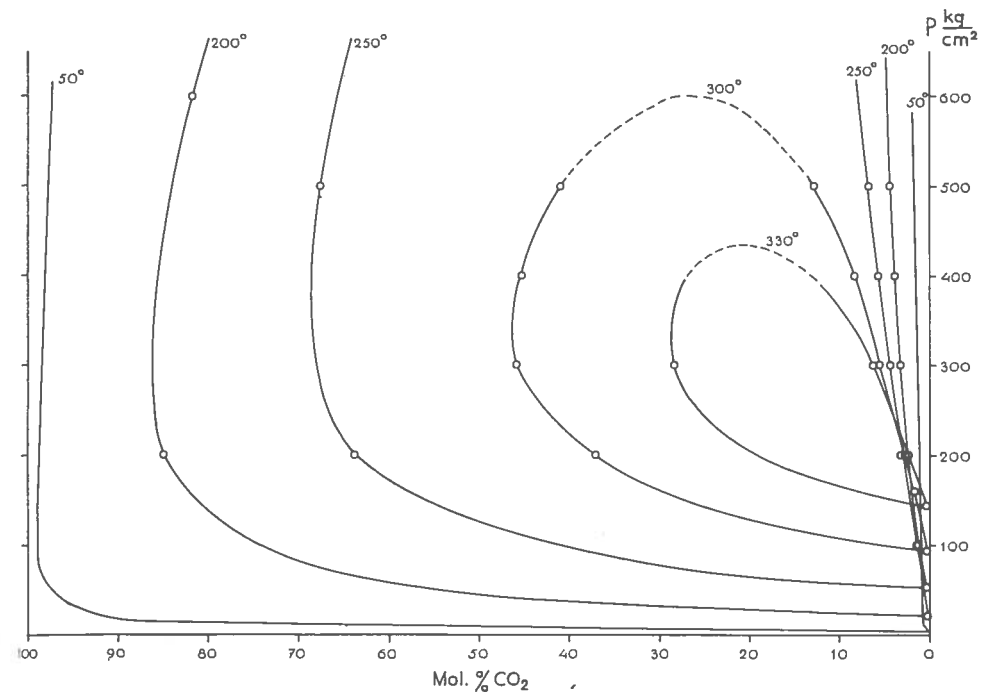


Fig. 11. The system H₂O-CO₂ at temperatures above the critical temperature of CO₂ according to data of Wiebe and Gaddy (1939) and Malinin (1959).

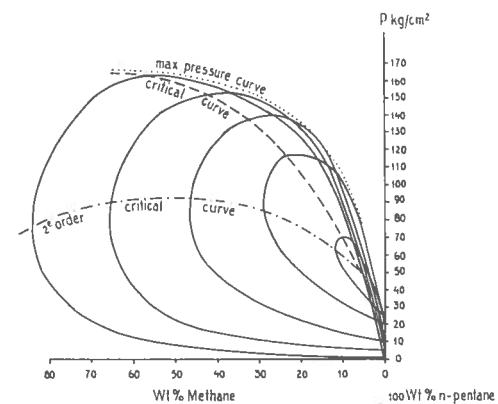


Fig. 12. Temperature and composition range in which retrograde condensation may occur with the system methane-n-pentane, according to Sage et al. (1942). The curves refer to the 38°, 71°, 104°, 138° and 171° C isotherms.

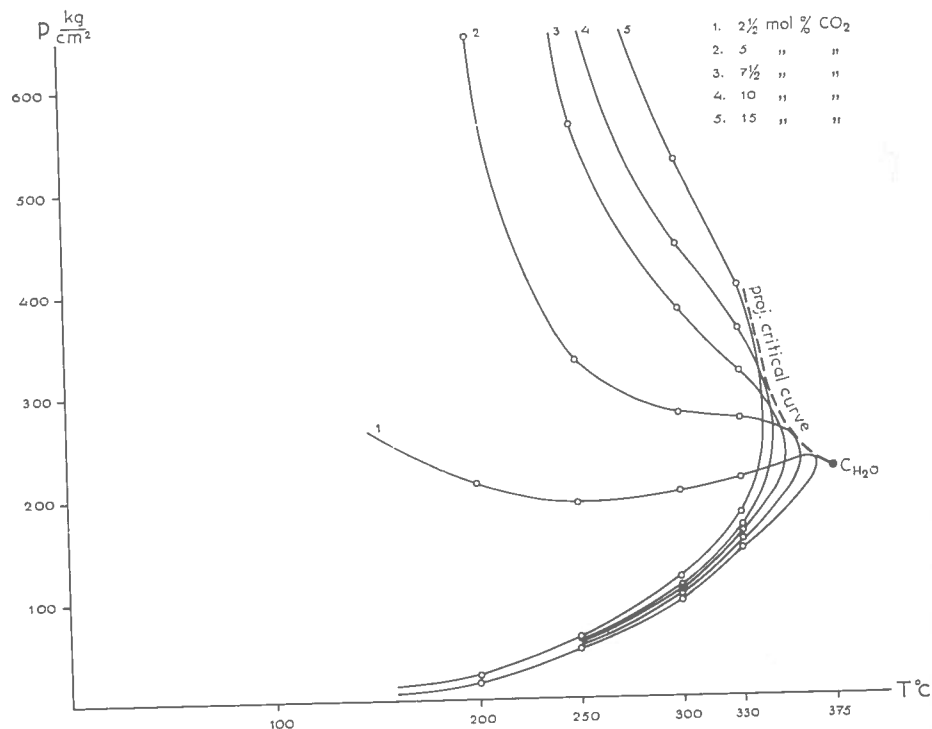


Fig. 13. Position of the critical curve of the system H_2O-CO_2 for solutions of 2.5 to 15 mol. % CO_2 .

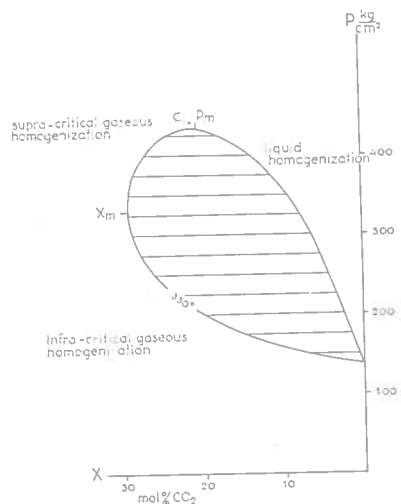


Fig. 14. The 330° -isotherm of the system CO_2-H_2O . The term supracritical gaseous homogenization refers to the phase transformation such as it is observed in the inclusions.

about 430 kg/cm^2). The trend of the 200° and 250° C isotherms suggest, that even if there exists continuity between the boiling point and the condensation point branches of the boundary curve, this must occur far beyond the pressure scope of the experiments ($> 1000 \text{ kg/cm}^2$).

The curves of Malinin, seen from the view point of solubility of gas in liquid, are very similar to those obtained by the petroleum-chemists of the Pasadena Institute of Technology in the years 1935-1945: Kay (1940), Sage et al. (1940), Sage et al. (1942) and many others.

The latter provide detailed information on the phase relations of systems in which natural gases (such as methane and ethane) and less volatile petroleum constituents (pentane and hexane) are involved (fig. 12).

15 Critical phenomena in a system of two incompletely miscible components

We may consider one of these systems more closely for the study of critical phenomena, a feature that can hardly be described from the rather scanty data on which the Malinin curves are based. The methane-n-pentane system of Sage et al. (1942) is represented in figure 12.

We note the position of the critical curve (of the first order) to be very close to, or coincident with the maximum pressure curve, a condition that generally occurs, if the critical pressure of the pure system exceeds considerably the critical pressures of the pure components.

Caubet (1902) deals with the construction of the critical curve and its theoretical implications making use of PT sections (fig. 13). Only in the case of border curves passing in the PT section through maximum and minimum values a position of the critical point on the condensation points branch underneath the second order critical point may occur, as opposed to the general positions: namely between the second order critical point and the maximum pressure point, or coincident with the maximum pressure point.

Returning to Sage's diagram, its most striking feature is the wide range of composition that may show a retrograde condensation of n-pentane-rich liquid on isothermal expansion. Even at high temperatures this phenomenon can be expected to occur, but it will be very common in the low temperature range.

This statement implies that retrograde phenomena will be very common with all systems featuring on falling temperature a rapid increase of the critical pressure, exceeding considerably the critical pressures of the pure components, which feature is accompanied by a corresponding change of the boundary surface.

16 Retrograde condensation with the system $CO_2 - H_2O$

Although on falling temperature the system $CO_2 - H_2O$ also displays a rapid growth of the field of co-existing liquid and vapour phases, the interval, in which retrograde condensation may occur, is only limited to the high temperature range because of the lack of continuity of the boundary curves below 250° .

One may ask what will be the practical interest of retrograde

condensation with regard to the CO₂ - H₂O filled inclusions. The answer should be that, actually, we are not free to lower pressure without affecting the temperature or vice versa, since we are dealing with a constant volume system, and in view of the change of composition of the phases, we have only one degree of freedom left and therefore temperature changes are accompanied by altering pressures. The relation is such that on lowering the temperature the pressure will also fall. Hence, if we have to do with such a CO₂ - H₂O composition above 250° C that on isothermal expansion should have brought on the condensation of a second phase, we are strictly speaking, not entitled to call the condensation occurring on decrease of pressure accompanied by cooling a retrograde one (Kahn, 1940), for condensation is a normal result of cooling.

Yet, we may compare this condensation from a supra-critical fluid (gaseous) phase with retrograde condensation, in order to distinguish this phenomenon from the normal condensation from an infra-critical gaseous phase (fig. 14).

17 Infra- and supra-critical gaseous homogenization with CO₂-containing fluid inclusions

We may summarize the conclusions that have been drawn from the behaviour of gas-liquid solutions within the critical region, by stating that on both sides of the boundary surface homogeneous gas phases occur, and a homogenization of fluid inclusions into a gaseous phase may be infra- as well supra-critical (fig. 14).

Especially the supra-critical gaseous homogenization is a possibility not envisaged by the authors dealing theoretically with the behaviour of inclusions on heating (Cameron, 1953).

The possibility of infra-critical homogenization is overlooked by Smith (1959) and Little (1955), when they used the presence of two types of primary inclusions, one homogenizing into a liquid phase, and the other homogenizing into a gaseous phase, for the direct measurement of crystallization temperatures. Their method is based on the reasoning, that if a mineral grows under a two-phase condition, and inclusions having different homogenization phases but equal homogenization temperatures are observed, that pair of inclusions, yielding the lowest equal homogenization temperature, should have entrapped only one of the phases present at the moment of crystallization. Provided equilibrium exists between both phases at entrapment and provided both phases have originated from a homogeneous fluid, equal homogenization temperature implies equal pressure conditions, and hence no pressure correction is necessary for determining crystallization temperatures.

This apart from the fundamental correction for the greater size of the inclusions at the end of the homogenization test, as compared with the size at the moment of crystallization, the external pressure on the mineral during the experiment being at least several hundreds of bars less than the pressure prevailing during crystallization.

Smith's method of determination of crystallization temperature will fail to be correct if the phases from which the mineral has crystallized did not originate from a homogeneous solution, as may be the case in that area of the PTX diagram where the

boundary curves are not continuous. In these instances an equal homogenization temperature of two types of inclusion is merely coincidental, both phases have different geneses.

The inclusions described by Brinck (1955) in the gold-bearing quartz veins of Suriname have to be looked at in this light, too, for many of them consist of almost pure carbon dioxide and show homogenization temperature far below other, also primary ones that contain observable amounts of water. If both were homogeneous at the moment of entrapment (constant ratio's between the phases at room temperature point to it), the two-phase system from which this quartz has crystallized must have been a kind of mechanical mixture. In such a case pressure corrections have to be applied.

18 Gaseous and liquid homogenization as a function of the inclusion's composition

Generally it is assumed that a close relation exists between the ratio of water to the CO₂-rich phase at 31° C, and the phase in which the inclusions homogenize on heating. The authors, Cameron (1953), Deicha (1955) and Brinck (1955) agree that the critical composition is reached at a ratio of about 1 : 1, under which the CO₂-rich inclusions will homogenize into a gaseous phase, whereas the water rich inclusions do so in the liquid phase.

This statement, however, is a generalization, since the critical composition depends on three factors about which it is difficult to make observations at room temperature. They comprise: the position of the critical point on the boundary curves, the filling degree with water and the CO₂-concentration. Two of these factors are independently variable. Therefore, a PTV-diagram has to be constructed, in order to predict the critical filling degree for a fixed CO₂-concentration, or vice versa. The pressure-temperature-volume relations for several CO₂-concentrations will be described in the next paragraphs. Yermakov (1957) investigated the relation between homogenization phase and filling degree, but did not draw systems containing carbon dioxide into consideration.

19 The temperature-pressure relations with constant volume in one- and two-components system. The VX diagrams

Coming to the point of interpretation of homogenization data and the way in which this process occurs, a certain knowledge about the relation between pressure and temperature will be necessary.

As with the one-component system this relation should be a function of the volume. We saw (par. 3) the one-component system reacting by condensation on adiabatic reduction of volume, during which process the pressure remained constant.

However, according to the rule of Konowalov, condensation of a two-component system will give a liquid of a composition different from that of the vapour phase. Consequently, the liquid's composition will vary during the condensation process. This variation is represented by a volume-composition-diagram.

A VX-diagram for completely miscible liquids is represented by fig. 15.

The line $G_A - G_B$ denotes the moments at which, at a fixed temperature, a reduction of volume results into condensation. A gaseous mixture of composition X_2 will start to condense with a liquid of composition L_1 , whereas the process will finish with the complete condensation of a liquid of composition L_4 .

Vapour and liquid phases being in equilibrium with each other are linked by tie-lines. These tie-lines are not empirically drawn, but can be calculated. For a complete thermodynamical treatise on this subject the reader is referred to the textbooks of Bakhuis Roozeboom (1904, part II), Kuenen (1906) and Kortüm et al. (1952, chapter II).

From the trend of the tie-lines the rate of increase of pressure during the condensation process can be derived, since the condensed phase will become gradually richer in the most volatile component and this is accompanied by an increment of the vapour pressure. The angle, at which the X-lines intersect the tie-lines, is indicative for the rate of pressure increase: the greater the angle, the sharper the pressure rise (fig. 16).

Increase of temperature will reduce the condensation process. The critical point of one of the components (for instance A) is marked by the contraction of the condensation and liquid composition curves into one point (fig. 17). Continued rise of temperature will cause the loop-shaped curves to move to the B-axis (fig. 17 and 18).

The critical points are given by the situation that the tie-lines in these points are tangent to the curve. Retrograde phenomena are equally demonstrated by these supra-critical VX-diagrams (fig. 22), since the tie-lines also provide information about the relative amounts of a phase present in a certain volume, in the same manner as do the tie-lines of the PX-diagram.

20 VX-diagrams of a partly miscible two-component system

In the case of water-carbon dioxide we are dealing with a system having only partial miscibility. This incomplete miscibility is represented by a triangular gap in the VX-diagram. A diagram of such a hypothetical two-component system is represented by fig. 19. For a temperature corresponding with the critical temperature of the most volatile component (for instance A) the curves will separate from the A-axis. The temperature at which the triangular gap disappears from the diagram depends on whether both liquids become identical first (fig. 20a) or whether one liquid and a gaseous phase do so first (fig. 20b). The latter figure applies to the system $CO_2 - H_2O$, where homogenization between the gaseous and the CO_2 -rich liquid takes place, and the supra-critical CO_2 -rich phase remains only slightly miscible with the H_2O -rich liquid phase. The variation of the VX-diagrams with temperature is given by fig. 21, 22 and 23.

As demonstrated with the VX-diagram for completely miscible systems, the angle between the tie-lines and the composition-line provides information about the pressure increase. A water-rich system of composition X_1 , for instance, (fig. 24) on decrease of volume will display a slight pressure increase

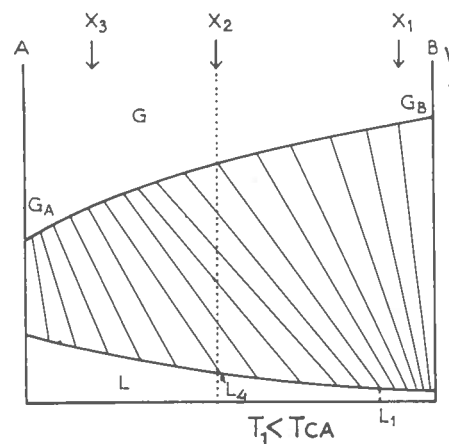


Fig. 15. VX-diagram of a completely miscible binary system at a temperature lower than the critical temperature of the most volatile component.

Fig. 16. Pressure increase on isothermal volume reduction of three different solutions corresponding with those of figure 15.

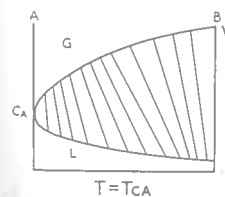
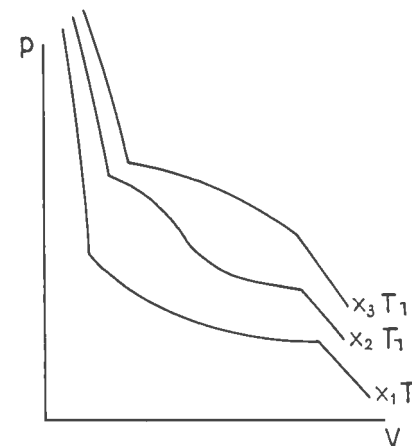


Fig. 17. VX-diagram of a completely miscible binary system at the critical temperature of the most volatile component.

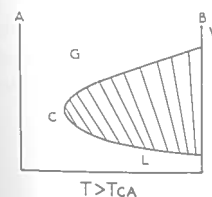


Fig. 18. VX-diagram of a completely miscible binary system above the critical temperature of the most volatile component.

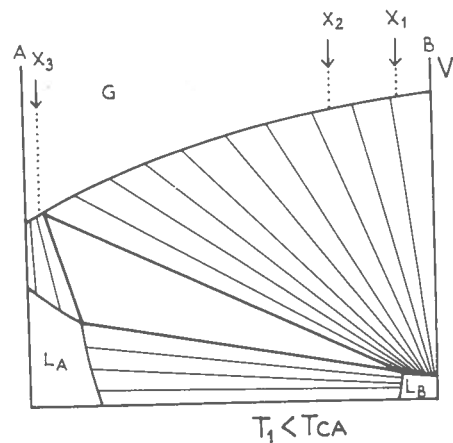


Fig. 19. VX-diagram of a partly miscible binary system below the critical temperature of the most volatile component (A).

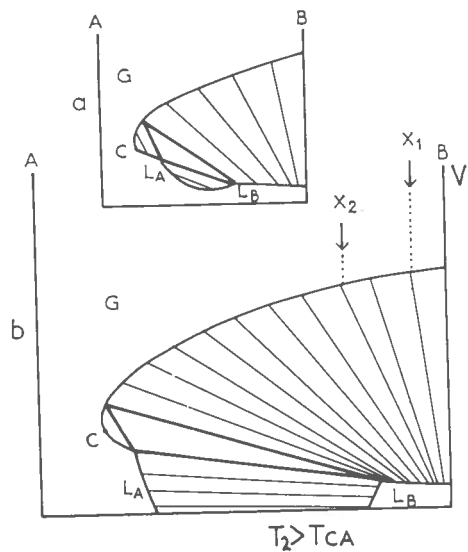


Fig. 20. VX-diagram of a partly miscible binary system above the critical temperature of the most volatile component, close to the temperature at which the composition of the A-rich liquid equals that of the gaseous phase. The inset-figure refers to the case that the composition of the A-rich liquid equals that of the B-rich liquid.

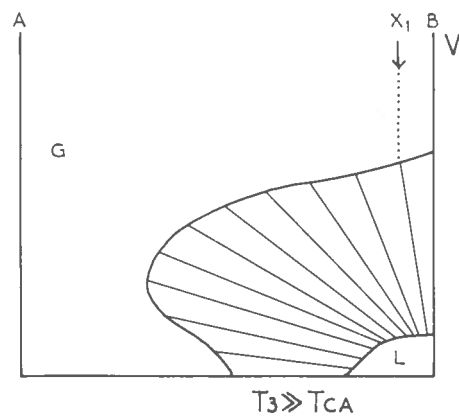


Fig. 21. VX-diagram of a partly miscible system at a temperature higher than the three-phase-temperature.

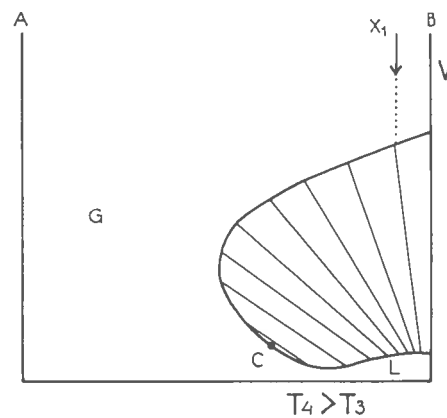


Fig. 22. VX-diagram of an originally partly miscible binary system at a temperature at which miscibility becomes complete.

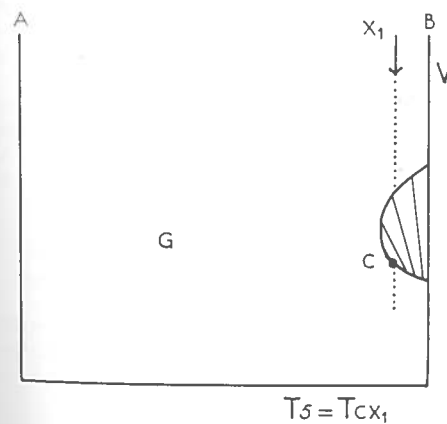


Fig. 23. VX-diagram of a binary system at the critical temperature of a solution of composition X_1 .

Fig. 24. Rate of pressure increase on isothermal volume reduction of solutions and mixtures of compositions corresponding with those of figure 19.

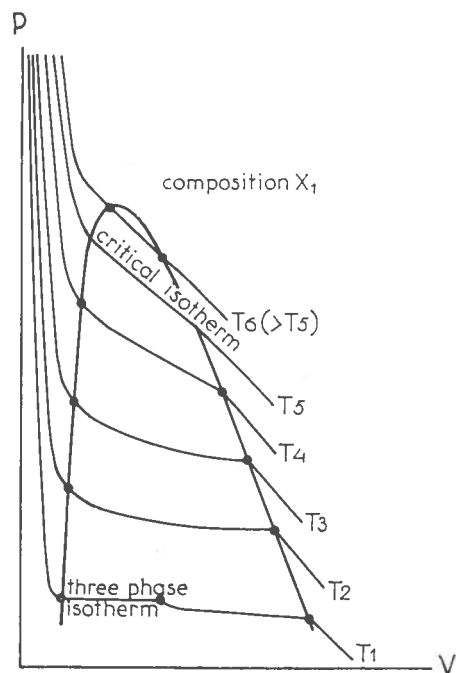
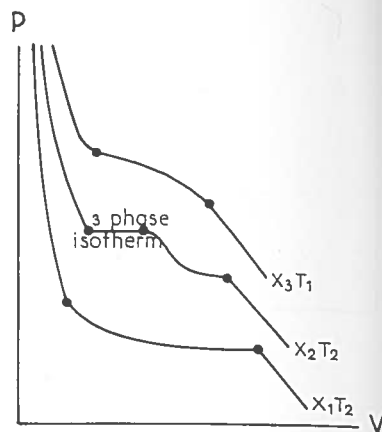


Fig. 25. Rate of pressure increase on isothermal volume reduction of a partly miscible binary system at temperatures corresponding with those of the figures 19, 20, 21, 22 and 23. The kink-points in the curves are indicated by dots.

during the begin of the condensation process. The increase will be more pronounced towards the end of the process, and will become even very steep at the moment the vapour phase has vanished. A system containing substantial amounts of carbon dioxide (X_3 , fig. 24) will show a more conspicuous pressure rise than is the case with the water-rich system right from the moment of the first appearance of the liquid phase. The rate of pressure increase, however, will be fairly constant during the condensation process.

21 The PV-diagrams for unary and binary systems

The PV-relations in a one-component system are known by means of sections at a fixed temperature value of the PTV blockdiagram. A PTV diagram of a two-component system above the critical temperature of one of its components, however, has not yet been constructed as far as known to the author. We will try to evaluate theoretically the curves of such a diagram for some $H_2O - CO_2$ systems.

Starting with the PV-curves for a system of composition X_1 (fig. 25) we will note that the pressure increase on reduction of volume at a constant temperature resembles a hyperbola having two knick points, one at the moment condensation starts, and another when condensation has finished. At higher temperatures the knicking of the curves at the phase transition points becomes less marked, and will disappear completely at the critical temperature (fig. 25). The latter feature represents another characteristic of the critical state (Caubet, 1902).

The PV-curves of a system of composition X_2 show a sharp rise of the pressure from the very start of condensation, whereas the pressure increase tends to diminish towards the end of the condensation process, in particular at higher temperatures (fig. 24).

We may regard the PV-curves as sections of a three dimensional PTV-diagram. With an unary system that part of the diagram denoting equilibrium between liquid and vapour phases is parallel to the V-axis, and therefore all PV-sections cutting the diagram in its two-phase area are partly parallel to the V-axis. Obviously, the isothermal reduction of volume is also isobaric, during the condensation process.

The PV-diagrams of binary systems have also to be seen as sections of a PTV-diagram. The non-isobaric course of the PV-curves under two-phase conditions, however, means that the part of the diagram representing liquid-vapour equilibrium does not form any longer a plane parallel to the V-axis, but is a rather complicated surface. Its deviation from the cylindrical plane of the one component system depends more or less on the rate of pressure increase.

22 The rate of pressure increase during the fluid inclusion's homogenization test

The interest of the rate of pressure increase during the homogenization test is given by the frequently occurring necessity to establish a correction factor for inferring the

actual crystallization temperature from the homogenization temperature. If, for instance, it is known from geological considerations that the hydrostatic pressure at the moment of crystallization has been higher than the pressure at the point where the inclusion's isochore intersects the boundary surface, the actual crystallization temperature is given by the abscissa of the point at which the continued course of the isochore attains the geologically presumed pressure value on the ordinate.

These pressure corrections are easily applied for one-component inclusions, since the courses of the isochores are, once homogenization has been achieved, linear functions and are merely governed by the densities of vapour or liquid at varying temperatures and pressures, connecting points of equal density. Kennedy (1950b, 1954) gives extensive data on the densities of CO₂ and H₂O for those pressure and temperature values that are of interest to the geologist (100 - 1200° C and 25 - 1400 bars).

For the system CO₂ - H₂O it should be possible to calculate the total pressure as sum of the partial pressures according to Dalton's law, if the relative volume is large enough to accommodate the components at very low density. This condition, however, is not fulfilled by fluid inclusions and, in a general way, not with any geological process. Therefore, Khitarov and Malinin (1956b) have experimentally determined the total vapour pressure exerted by systems of varying CO₂ - concentrations (up to 40%) for different filling degree with water (0,2 to 0,7 part) at temperatures varying from 100 to 400° C. They noticed a marked positive deviation from Dalton's law, the total pressure being higher than the sum of the partial pressures. This pressure difference is linearly proportional to the filling degree with water, the CO₂-content and the temperature, and thus permits the extrapolation of pressure-temperature relations for higher values than those experimentally determined, making use of Kennedy's tables.

Having inferred the course of the PV-isochores for systems of different CO₂-concentrations from theoretical considerations (par. 20 and par. 21), one is able to construct the PTV-diagram with the help of the experimental and extrapolated data of Khitarov (1956b). In a schematic way this has been done for a system corresponding with a water-rich inclusion (X₁, fig. 26) and another corresponding with an inclusion containing substantial amounts of CO₂ (X₂, fig. 27). X₁ and X₂ correspond with the compositions of fig. 19.

The PTV-diagram provides the only means for establishing the critical filling degree for a certain H₂O : CO₂ ratio, since the critical point on the two-phase boundary curve is not the maximum pressure or temperature point, but the point of intersection between the boundary curve and the critical PV-isotherm. As mentioned in par. 21 the critical PV-isotherm is the isotherm characterized by the absence of knick-points at the moment of phase transition. Hence, the filling degrees which are critical with respect to the transition between liquid or gaseous homogenization vary between 0,3 for pure water to 0,4 for concentrations of 20 mol. % CO₂.

For the construction, however, of the complete isochores more information than that furnished by Khitarov is necessary, since his data do not inform us about the pressure-temperature relations for temperatures lower than 100° C. For these low

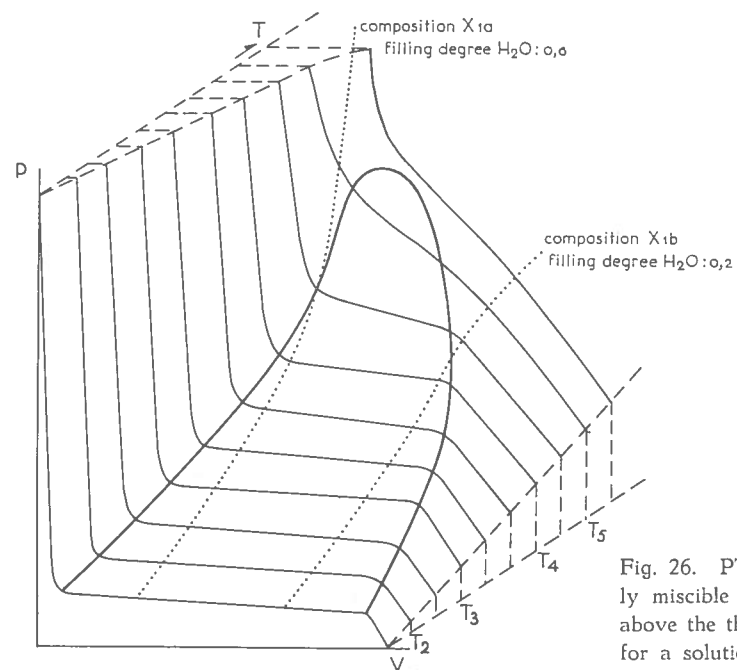


Fig. 26. PTV-diagram of a partly miscible binary system heated above the three-phase temperature for a solution corresponding with X₁ of figure 19.

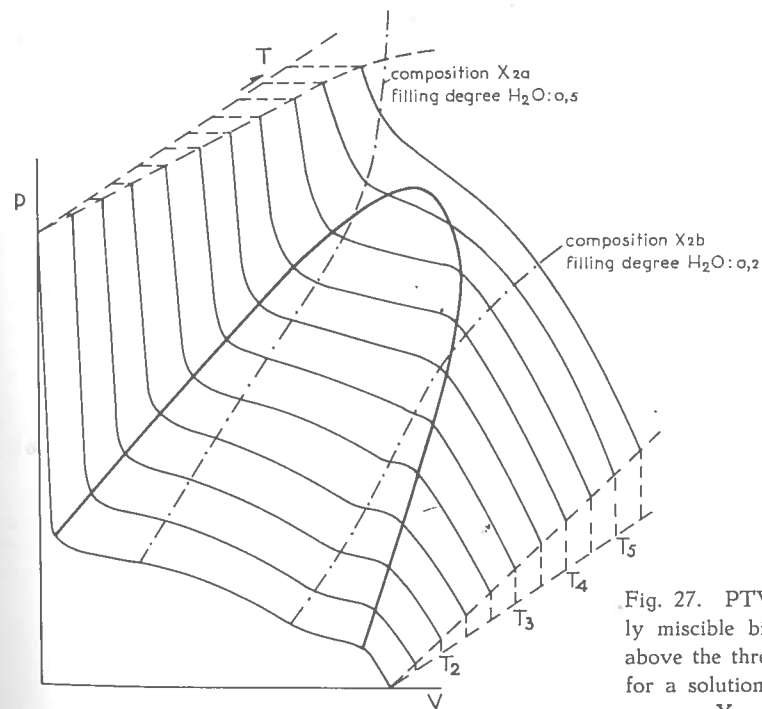


Fig. 27. PTV-diagram of a partly miscible binary system heated above the three-phase temperature for a solution corresponding with X₂ of figure 19.

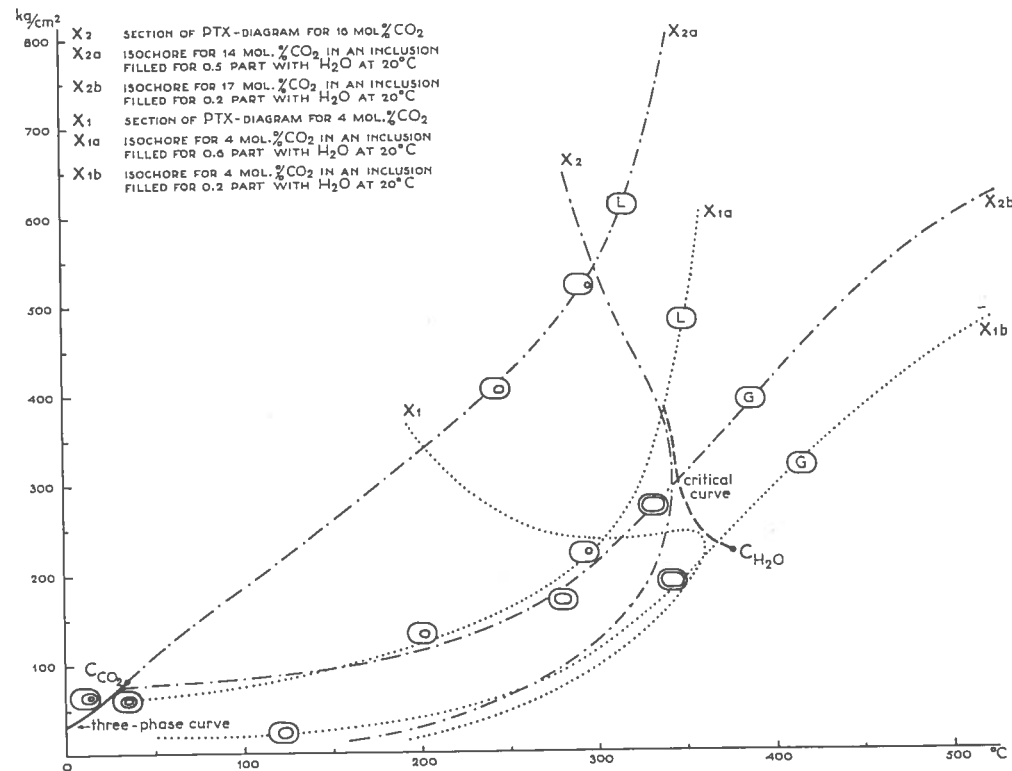


Fig. 28. Relation between inclusion-type and mode of homogenization as shown by the isochores. These correspond with two types of composition and filling degree.

temperatures the deviation from Dalton's law is small, because of the low total pressure and the small water vapour pressure. Moreover, if three phases are present at 31° C, or less, the pressure-temperature relations are precisely known, irrespective of the inclusion's composition. The position of the three-phase line in the PT-diagram differs only slightly from the two-phase line of CO₂ as represented in fig. 30.

A construction of four isochores corresponding with two types of composition and two filling degrees with water, is represented by fig. 28.

The schematically drawn inclusions denote the process of homogenization. From the diagram it appears that in case of low CO₂-concentrations it will be very difficult to predict the kind of phase transformation at homogenization judging from the inclusion's content at room temperature.

23 Decrepiation as a function of pressure increase

If factors controlling decrepitation, such as shape, size and position of the inclusions can be eliminated, for instance, by means of a comparative study, then the difference between decrepitation and homogenization temperatures might be seen as a parameter for the increase of pressure on heating. Decrepiation will occur in the steep part of the PT-isochores. Hence, it will occur with CO₂-rich inclusions earlier, under otherwise equal conditions, than with H₂O-rich inclusions. Special attention has been paid by the author to the difference between homogenization and decrepitation temperatures, and it has been shown that the theoretical curves of pressure increase are confirmed by the observations.

24 The failure of the cooling test to produce a third phase with CO₂ containing inclusions below 31 C°. The "corps spherique" of Deicha.

The slow decrease of pressure occurring in the 100°-0° C range with inclusions containing not more than 5 mol. % CO₂ may imply an explanation why inclusions, which reveal appreciable amounts of CO₂ with the gas test, fail to show a second liquid phase even when cooled below 0° C. Apparently the PT-isochore does not intersect the three-phase line within the experimental temperature range. Deicha (1955) called the attention to this phenomenon and proposed to speak of a "spherical body" to denote a vapour phase which is likely to contain appreciable amounts of CO₂.

Finally the author wants to remark, that by recording homogenization temperatures alone, one is greatly underrating the possibilities provided by the inclusions for a better understanding of hydrothermal and pegmatitic ore genesis.

Instrumental aspects of the fluid inclusions investigation

25 The gas test and sample selection

Because of the small size of the inclusions, ranging from 100 to 1 micron, all investigations have to be done with the microscope, at high magnifications, the gas test excepted. The gas test is performed on the microscope stage between two solid glass plates with the sample placed on a tiny square glass support embedded in an oily substance. Glycerine is an ideal immersion liquid, since its viscosity is high enough to keep the released gas bubble within the liquid, and its surface tension is not so strong as to prohibit the small bubbles released by each inclusion individually to unite into a large observable one.

For getting a general picture of size, shape and repartition of the inclusions, and for distinguishing between primary and secondary inclusions the application of mounted grains and thin sections of about 0,06 mm (quartz - first order red I) thickness is most convenient. From these preparations the type of inclusions is selected that will be subjected to the heating stage test. The use of polarized light to determine the crystalligraphical orientation in the specimen investigated may help to recognize primary inclusions.

26 The heating stage

The effects of heating inclusions were studied with the aid of a Leitz microscope-heating stage, type Weygand. This stage is originally designed for the determination of melting points, crystallization phenomena and other physico-chemical reactions, whereby only low magnifications are necessary.

The use of the stage as a heating device for the study, of inclusions however, involves some modifications to be made, the use of high magnifications being inevitable.

The selection of exceptionally large inclusions may possibly cause a deviation from the average. High magnifications, however, imply a short working distance between object and objective, a condition that is hardly compatible with the high temperatures needed for homogenization tests. Cooling the objective with air, or carbon dioxide, did not bring on the effect desired, the air flow caused heating of the whole microscope. Moreover, the abrupt temperature gradient between objective and object induced uncertainties about the actual temperature of the object.

The modifications, that have been made to the stage include the mounting of a short-focus condenser lens immediately below the specimen holder, in order to overcome the dark shadows caused by the inclusions situated below and above the focal plane. Moreover, the original heating cell consisting of a coil of asbest coated resistance wire has been replaced by a spirally wound coil mounted in a circular mica-coated cell, thus enabling higher temperatures to be reached (370° C) at an increased rate. The coil is fed by an adjustable low-voltage transformer in order to keep the rate of temperature increase at a constant value.

27 Accuracy of the temperatures measured

The latter provision has to be made for applying the right correction factor.

Because the temperature is measured with a thermometer inserted in the specimen holder and the heat is transferred to the object along a glass slide, the temperature measured might not be equal to the actual temperature of the specimen on the glass slide. Thus, a correction table has to be made. This has been done by Mr. Popper in the Physics Laboratory of Leiden University, using two thermocouples one inserted in the thermometer hole and another situated on the glass slide. The results are given in a diagram (fig. 29).

The author utilized a rate of temperature increase of 17° per minute. This rate is slow enough to observe phase transitions with an accuracy of $\pm 3^\circ$ C, and high enough to prevent a possibly harmful heating of the whole microscope.

An old metal mounted, not cemented P₅ (30x) objective of Leitz, appeared to be very useful. With the special condenser system and highly magnifying eyepieces (15x and 25x), the resolving power is such that even small inclusions (10 micron) can be observed.

Cooling of the specimen can be done by water streaming through the circular compartment around the heating cell, or if lower temperatures are necessary by carbon dioxide. With a normal compressed carbon dioxide cylinder temperatures of 15° C below zero are easily obtained.

28 Preparation of the specimen

The specimen for investigation with the heating stage have been prepared in the following way. After selection of the inclusion type to be studied, flat chips of the mineral are investigated for their fluid inclusion content, and if appearing to meet the requirements, are mounted with Araldite 101 (Ciba) on a glass slide, and covered by another slide. The sample thus prepared is inserted in the holder with as many centrally perforated copperslides as are necessary to fill the holder in order to use the specimen's coverglass as the heating stage's upper window.

Araldite 101 is very appropriate as a mounting medium, since its evaporation is only slight and, as a result of polymerization it gains viscosity on repeated heating. Moreover the viscosity at high temperatures is low enough to enable the decrepitation gas bubbles to disappear from the focus. Carbonization only starts above 340° C.

Evaluation of the results

29 Mode of representation of the results

The microscopic observations carried out on the inclusions are listed in the tabulated synopses of the descriptive chapters. The figure give information about shape, size and approximate

filling degree at room temperature. The actual filling degree is difficult to estimate from the picture since the inclusions may be highly concave. Concerning the size and shape depicted, it must be noted that generally representative inclusion types are featured. The same is true for the temperatures of phase changes and decrepitation: they, too, represent average values. If only one temperature value is mentioned, this means that the frequency distribution of the temperatures measured displays a definite maximum and the deviating values do not differ more than 10°C from this mode. These deviations may be due to observational errors or retardation effects. Because of the retardation effects with phase transition (metastable phases) only the values obtained from heating are mutually comparable.

30. Transitions between primary and secondary inclusions, and primary inclusions of varying nature

Many crystals show almost identical inclusions to have homogenization temperatures so different that a fundamental divergence of composition must be assumed. The author's first idea for explaining this phenomenon was to suppose an inhomogeneous nature of the mother liquid at the moment of entrapment. Such crystallization from an inhomogeneous mother liquid has been described by Smith (1959). He records the inclusion's composition to range from the entrapment of a pure gaseous phase on the one hand, to a mere liquid phase on the other one, both types being linked by all kinds of intermediate stages. Provided the two-phase state of the mother liquid is a result of cooling of a primordial homogeneous fluid, and not a mechanical mixture, the range of homogenization temperature will have a limited extent. Although, theoretically, equilibrium between both phases may exist down to very low temperatures. The densities, however, of both phases at, for instance, 200°C are so different that a statistically equal distribution of both phases in the mother liquid becomes highly improbable.

It may even be asked if crystallization from an inhomogeneous fluid may be invoked at all as a possible explanation for the genesis of the inclusion-type described above. Especially in the case of vein minerals the author is sceptical about the presumed frequent occurrence of inhomogeneous media in a time-interval long enough to get entrapped during the whole growth process of the crystals.

His sceptical attitude results from observations on artificially grown crystals like ammonium-dihydrogen-phosphate and triglycine-sulphate.

Many of these crystals growing from aqueous solutions show zonally arranged inclusions, among which quite a few are partly filled with air bubbles. These inclusions are to be attributed to irregularities in the thermostatic control of the gradually cooling solution accompanied by supersaturation phenomena. These factors interfere with an even development of the crystals: cavities are the result. The solution, however, does not contain air in the form of bubbles, hence these must originate from the very disturbance of equilibrium itself. Apparently, the irregularly growing surface of the crystals

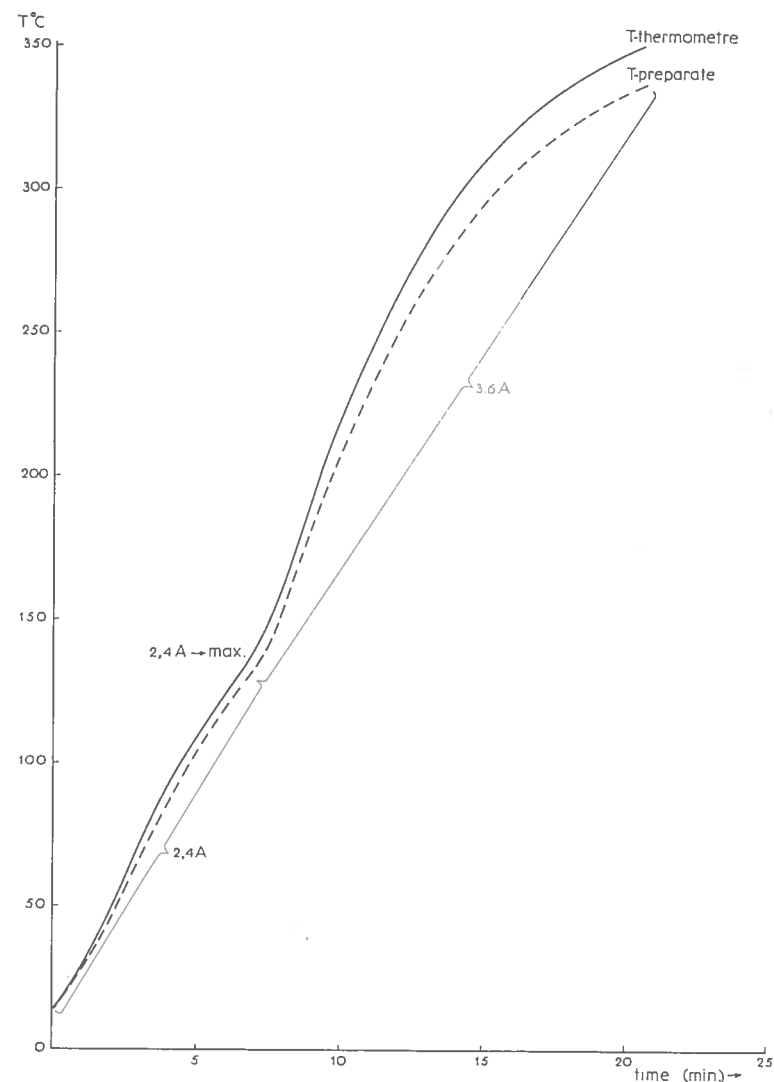


Fig. 29. Temperature differences between sample and thermometer with the Leitz-Weygand heating stage, expressed as function of time and temperature. The amperages refer to the strength of current used.

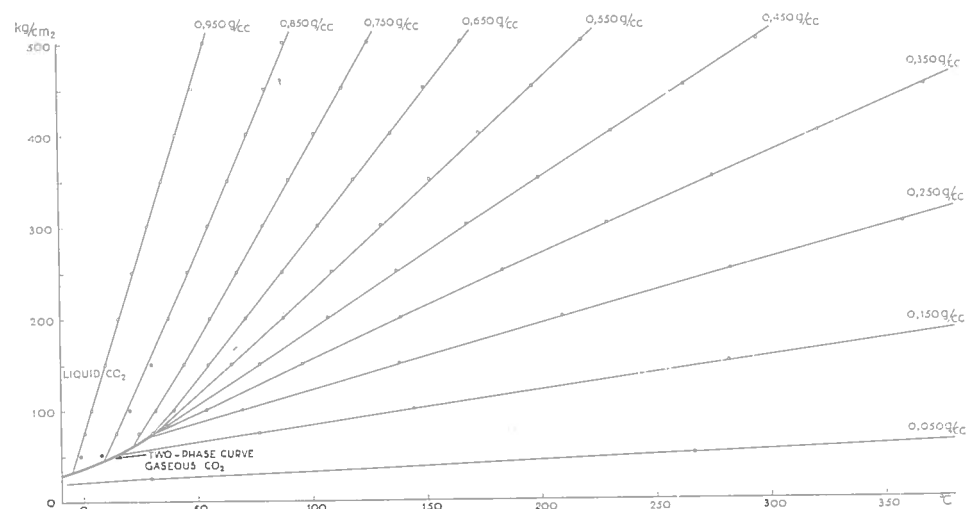


Fig. 30. Density of carbon dioxide, according to Kennedy (1954).

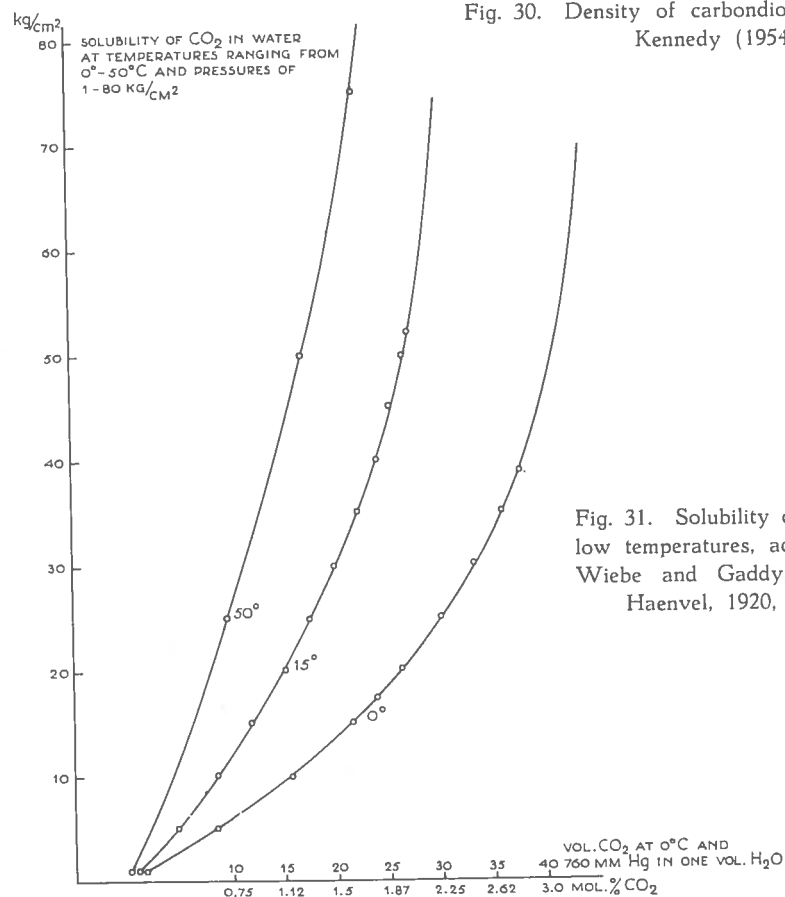


Fig. 31. Solubility of CO₂ in water at low temperatures, according to data of Wiebe and Gaddy, 1939 (50°) and Haenvel, 1920, (0° and 15°).

provides nuclei for the exsolution of air.

This process of entrapment of non-homogeneous matter from a homogeneous solution may also happen with the formation of inclusions of vein minerals. We may predict from the theoretical considerations that the process described above, if occurring, will be especially pronounced with those PTX-values where temperature changes have major effects, in particular in the critical part of the system.

Returning to the case of unequal homogenization temperatures of almost identical inclusions, we have also to consider the possibility of crystallization (and subsequently: formation of inclusions) during a certain temperature interval. Strong evidence for this possibility is given by the feature that some inclusions of obviously primary nature within one crystal are identical (equal content and homogenization temperature) with secondary ones of others. Such observations mean that the temperature interval of cooling is large enough to produce crystals with inclusions of observably different composition. Again we may presume these differences to be most pronounced with solutions of critical PTX-values.

31 Summary on the inclusions of the young vein quartz

Comparing the results of the quartz inclusions study, two types of inclusions are easily distinguished.

The first type is marked by a very particular series of features:

- a high homogenization temperatures
- b a rather wide range of homogenization temperatures
- c considerable amounts of CO₂ (about 30 vol. % at 31° C)
- d consistent appearance of a third phase between 20° and 31° C
- e the third phase to appear may be either a liquid CO₂ or a gaseous CO₂ phase
- f early decrepitation
- g relatively large size
- h moderately concave shape
- i few inclusions are empty
- k lack of stress effects of the host mineral

From the theoretical consideration we have learned to see this combination of features not as being merely coincidental, but as a consequence of the PTX-relations at the moment of entrapment. Hence we are in the position to deduce from the inclusion's data the circumstances under which the host minerals (quartz) have crystallized.

32 Composition of the fluids included in the young vein quartz

The composition can be estimated from the ratio H₂O-rich phase: CO₂-rich phase, the density of the CO₂-rich phase and the solubility of CO₂ in water at 31°. The water content of the CO₂-rich phase is negligible (according to data of Wiebe and Gaddy, 1939).

The CO₂: H₂O ratio varies between 1 : 1 and 1 : 2. The density of the CO₂-rich phase can be determined from the behaviour of

the inclusions when cooled below 31° C. The appearance of the CO₂-vapour phase between 10° and 25° points to a density of 0.850 - 0.750 gr/cm³, according to data of Kennedy (1954) (fig. 30).

Inclusions featuring the appearance of a third phase at such low temperatures are rare with the young vein quartz, if occurring, they are only incidental, and may be attributed to retardation of phase transition.

From the low temperature at which the third phase appears it may be concluded that a pressure higher than the three-phase pressure is present in the inclusions at 31° C. This pressure may amount to 80 kg/cm² or more. At these pressures and temperatures the quantity of CO₂ dissolved in the water-rich phase may be estimated at 2 mol. %, according to data of Haenel 1920 (fig. 31). Hence, the inclusion composition will range from 17-14 mol. % CO₂.

Much more common with the young vein quartz are inclusions featuring the appearance of a third (gaseous) phase on cooling between 31° and 25°.

Such behaviour of the inclusions content corresponds to a density of the CO₂-rich phase ranging from 0.75 to 0.45 gr/cm³.

0.45 gr/cm³ is about the critical density. Inclusions with a CO₂-rich phase of this density show a sudden disappearance of a third phase at 31° C. The exact critical density is only rarely met, more common is a sudden disappearance of a small vapour phase near the point where homogenization of the CO₂-content should have occurred.

Taking into account that 2 molecular percent of CO₂ is dissolved in the water-rich phase, the composition of these inclusions will range from 14 mol. % to 8.5 mol. % CO₂ for H₂O : CO₂ ratio's of about 2 : 1. Generally, the ratio is less, especially with inclusions of low or near to the critical density.

Only inclusions of quartz occurring close to the Triassic peneplain show the condensation of liquid CO₂ on cooling below 31° C. The condensation is visible as a rim around the gas bubble, of a refractive index lower than that of water. On further cooling the dimensions of the gas bubble decrease.

The condensation of liquid CO₂ means a lower density of the CO₂-rich phase than occurred with the previously described types. It ranges from 0.45 gr/cm³ to 0.25 gr/cm³. The H₂O/CO₂ ratio varies between 2 : 1 and 3 : 2. Since the PT - isochore intersects the three-phase line of the system H₂O-CO₂, these inclusions, too, possess at 31° C a pressure high enough to keep substantial amounts of CO₂ dissolved in the water-rich phase (about 2 mol. % at 31° C). The overall composition of inclusions featuring the condensation of liquid CO₂ as third phase will range from 8.5 to 6.5 mol. % CO₂.

As to the composition of the latter type it has to be mentioned that cubic salt crystals (probably NaCl) are commonly present.

The inclusions with higher CO₂-densities never contain these crystals. This may be due to the desalting effect of dissolved gases (Khitarov, 1959), only with low CO₂-densities appreciable amounts of alkali-chlorides can be dissolved (an estimated quantity of 10 vol. %).

This does not mean, however, that the inclusions with high CO₂ densities are devoid of any dissolved solid. It merely means

that the concentration of salt is not high enough to give rise to crystallization of an individual solid phase. Moreover it will be shown in the coming section that the high homogenization temperatures found for the high density inclusions does not agree with the experimental data. The actual homogenization temperatures exceeding for some 30° the temperatures at which the isochores for a given pressure and composition intersect the boundary surface of the system CO₂-H₂O. This feature should mainly be attributed to the solution of solid matter increasing the critical values of the system, such as has been established experimentally by Khitarov and Malinin (1959) for a CaCl₂-containing CO₂-H₂O system.

33 Pressure at crystallization and rate of pressure increase during the homogenization test

One of the most interesting conclusions that can be drawn from the inclusions behaviour on heating or cooling is the rate of pressure increase (or decrease) and the pressure at the moment of the fluid's entrapment by the host mineral, since the latter provide information about the geological conditions at the time of crystallization.

From the theoretical considerations we learned that the solution of highly volatile matter in a solvent will alter considerably the course of the isochores as compared with that of the solvent alone. A system consisting of water and its vapour, for instance, shows a slight increase of pressure on isovolumetric increment of temperature until the moment of disappearance of one of the phases, followed in the case of liquid homogenization by a very steep pressure increase (fig. 1 and 3). The solution of CO₂ causes a steeper start of the isochore, the pressure increase in the beginning being mainly governed by the compressed gas alone. In the higher temperature range, however, the total density of the CO₂- and water-filled inclusions becomes the predominant factor. The total density, however, may be less for large amounts of gas, than for a water-filled inclusion. Lower density means higher compressibility, from which follows that the isochore of a CO₂-rich inclusion will not show such a steep pressure increase once homogenization has been achieved, as with the pure water-filled inclusions of corresponding total filling degree, notwithstanding the steep start of the isochore (fig. 27).

This idea is confirmed by the high homogenization temperatures displayed by the CO₂-rich inclusions, since these values only can be realized in the low pressure range (350-450 kg/cm²) of the PTX-boundary surface (fig. 13).

There seems to exist an incompatibility between the high homogenization temperatures recorded with the CO₂-rich inclusions featuring the apparition of a gaseous phase on cooling between 31° and 25° (the L₁ L₂ G (25°) type) and the data of Malinin (1959), for according to his diagram temperatures of 330° - 360° are beyond the two phases area of a system consisting for 10-15 mol. % of CO₂ (fig. 28).

This inconsistency between the theoretical and the actual data of homogenization temperatures may result from retardation

(over-heating) and from the solution of solids. The latter increases the critical temperature and pressure of water. The presence of a saturated salt solution in inclusions of the low CO₂-density type has been mentioned before. Because of their similar position in paragenetic sequence, the presence of appreciable concentrations of dissolved salt may be assumed for all quartz inclusions of this suite.

The theoretical evaluation of the data of homogenization temperatures and phase transitions have given us an idea about the pressures occurring at the moment of homogenization, viz: ranging from 350-450 kg/cm². Geological evidence to support this idea comes from the observation that the height difference of 200 metres between the deposits of St. Joseph (nr. 45) and Grande Taillée (nr. 49), although they are closely spaced and both contain quartz and siderite of the same paragenetic suite, yet appears to be sufficient to produce with quartz an inclusion content of fundamentally different behaviour on cooling below 31° C, viz: quartz of the highest altitude featuring the appearance of liquid CO₂ (the L₁GL₂ (30°)-type), whereas the lowest deposit (Grande Taillée) displays a shrinking liquid CO₂-phase and the appearance of a CO₂-gas bubble (the L₁L₂G (25-31°)-type). This is not an incidental case but has been noticed with almost all quartz deposits close to the Triassic palaeo-surface.

This means that a load of some 200-300 metres of rock, corresponding with about 50-100 kg/cm², determines the character of the phase transformation of the inclusions. Such predominant control by slight pressure changes can only occur in the low pressure range, where 100 kg/cm² figures as a relatively large value.

A pressure drop of, for instance, 100 kg/cm² with a crystallization process occurring at 800 kg/cm² simply cannot accomplish a change of the course of the isochores so fundamental that the three-phase line is intersected in the area of gaseous CO₂ homogenization instead of the area of liquid homogenization.

Extrapolating between the 50-75 kg/cm² pressure value at 31° C and the 350-450 kg/cm² values at 260-350° C we may conclude to an even course of the isochores. The lower the CO₂ densities are at 31° C, the flatter becomes the slope of the isochores, and the lower are the ultimate homogenization pressures. The course of the isochores for inclusions of composition L₁L₂G (25°), L₁L₂G (31°) and L₁GL₂ (31°) are represented by fig. 32.

34 The crystallization temperature

The sensitivity of the composition of the liquid inclusions for a difference of hydrostatic pressure of some 100 kg/cm² means that crystallization occurred near the point of heterogenization of the mother liquid. A pressure drop of, for instance, 100 kg/cm² with a mineralizing solution of 9.5 mol. % CO₂-concentration and a total density corresponding with a filling degree with water at 20° C for 0.65 part, crystallizing at 600° C cannot accomplish a change of composition (fig. 32). Therefore pressure corrections need not to be applied with these inclusions for determining the actual crystallization temperature from the homogenization temperature.

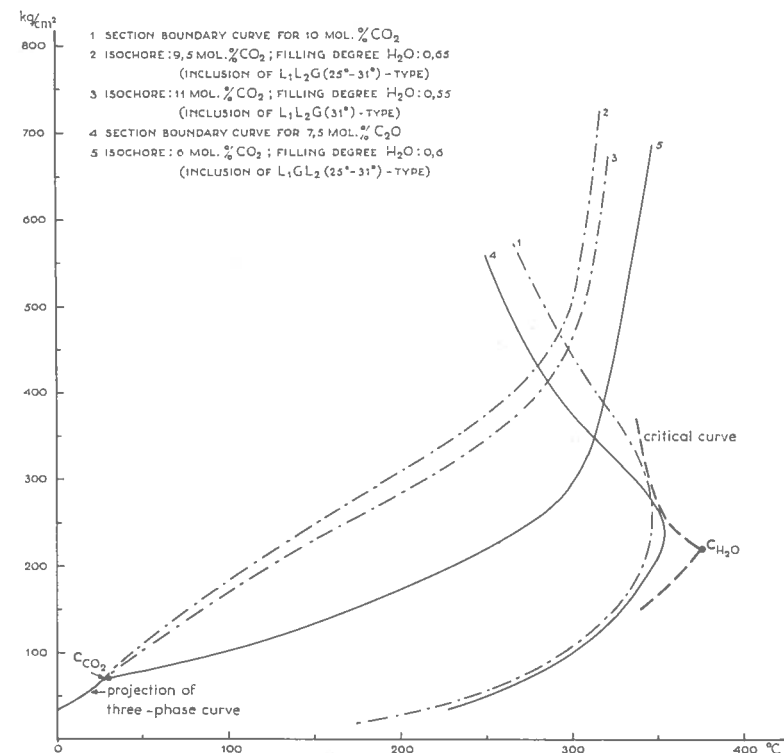


Fig. 32. Courses of the isochores for several CO₂-bearing inclusions, corresponding with those of the younger vein quartz.

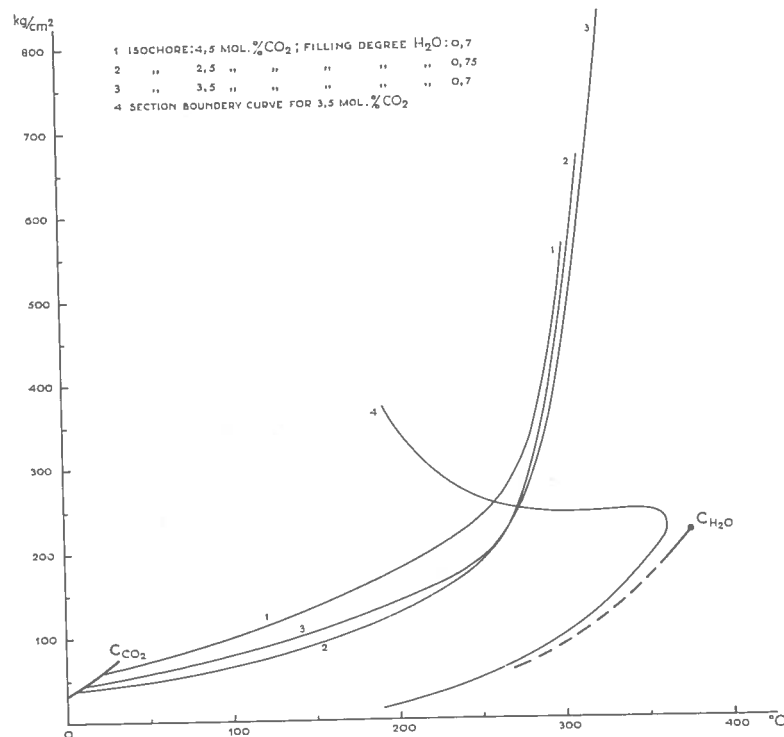


Fig. 33. Courses of the isochores for inclusions of low CO₂-content, corresponding with those of the older vein quartz.

Moreover, the wide range of homogenization temperatures, ranging from 270° - 360° for all inclusions of this type, and varying by some 40° for individual quartz crystals, implies that the entrapment took place at or shortly after the moment that the mother liquid has become heterogeneous. For only such crystallization conditions can account for the wide range of homogenization temperatures as effects of cooling during crystallization, or entrapment of inhomogeneous matter (Smith, 1959).

The latter possibility is not to be underestimated, since the very disturbance of equilibrium that caused the cavities at the growing crystal's surface may be responsible for unmixing of the solution, or conversely, the position of a gas bubble on the growing crystal surface may have inhibited its even development.

Hence we will suppose the actual crystallization temperatures to be represented by the lowest homogenization temperatures, ranging from 270° to 310° C. These are surprisingly high temperatures for the latest mineralization phase of an epithermal paragenesis, characterized by a small number of mineral species and a low trace-element content.

35 General crystallization conditions of the young vein quartz

Besides data of temperature and pressure the fluid inclusions give information about the position of the host in the paragenetic and tectonic sequence of events. The observation, for instance, of large inclusions filled with liquified gas in a vein quartz means that this mineral has been preserved from strong tectonic stress.

This implies, that if such inclusions are found in a mineral situated on a fault plane (such as the Vaujalaz deposit) the mineralization has occurred after the main tectonic phase. The Vaujalaz deposit, however, shows slight stress-effects, such as undulose extinction to a moderate degree, and a few cataclastic zones, which means that the quartz is not entirely post-kinematic.

That fault movements have occurred after the deposition of the young vein quartz is indicated by the fact that inclusions of the L₁GL₂ (25° - 31°)-type occur within the Belledonne's Inner Zone at altitudes of 2000-2300 metres, whereas the same type in the Outer Zone occurs only between 700 and 1400 metres, depending on the deposition of the Triassic peneplain. This difference in elevation corroborated by other geologic data, apparently has been brought on by the younger tectonic movements, which have been followed only by the gravitational gliding of the nappe of the Liassic border hills from the Belledonne Massif.

The latter event explains the absence of ore deposits in this nappe, which otherwise should have occurred there because of the common presence of ore deposits in the autochthonous Mesozoic overlying the La Mure Dôme.

The scarcity of secondary inclusions distinct from the primary ones by a compositional difference, such as should have been formed when mineralizing solutions pass for a second time through the same vein, designates the vein quartz as the youngest formation. Perhaps, the continuity that exists between primary and secondary inclusions must be seen as an indication

of the end of the mineralization process. Anyhow, also in this respect the fluid inclusions study confirms the age relation derived from textural and paragenetical relations.

Conclusions that can be derived from the fluid inclusion study, but which are only of local interest, are mentioned in the mineralogical sections of the descriptive chapters.

36 Inclusions of the old vein quartz

Contrary to the young vein quartz, the fluid inclusions of the older vein quartz do not display such conspicuous features.

They are characterized by:

- a a narrow range of moderately high homogenization temperatures
- b a rare apparition of a third phase on cooling below 31° C
- c regular content of gas under pressure
- d decrepitation at high temperatures only
- e relatively small size
- f highly concave or anastomotic shape
- g a host showing abundant signs of stress
- h many empty inclusions
- i predominance of secondary inclusions

37 Composition of fluids included in the old vein quartz

Although the crushing test provides evidence for the presence of carbon dioxide under pressure in the liquid inclusions, yet cooling below 31° (to -5° C) did not produce a perceptible condensation of a liquid CO_2 -phase, or the shrinkage of liquid CO_2 to form a vapour phase. Inclusions that do not feature the shrinkage of the liquid CO_2 phase on cooling between 31° C and 10° C must be very rare, since in view of their extremely high CO_2 -density, their isochores are so steep, (fig. 30) that theoretically, they will pass through a field of the PTX-diagram where the boundary curves are not continuous (fig. 11 and 13), and hence, miscibility between the water- and CO_2 -rich phase never will be achieved under geologically feasible conditions. If such high-density inclusions nevertheless show the apparition of a gaseous CO_2 -phase only at low temperatures (less than 10° C), this may, largely be due to effects of retardation of phase transition.

- Excluding the case of an extremely high CO_2 -densities, there are several possibilities that should be envisaged to explain the absence of a liquid CO_2 -phase on cooling below 31° C:
- the actual CO_2 -content is so small that any condensed CO_2 -phase is not perceptible
 - as a result of pressure present in the inclusions at room temperature considerable amounts of CO_2 are solved in the H_2O -rich liquid phase
 - the inclusion's isochore does not intersect the three phase line

Although in certain instances the first possibility cannot be excluded, it is improbable that the common release of gas by the crushing test should be caused by a very small CO_2 -content,

since the inclusions are neither exceedingly numerous, nor are they so large that the crushing test affects all inclusions. On the contrary, they generally are rather small and the crystal fragments show many inclusions that have been left unimpaired by the test. Thus the small size of the inclusions renders it difficult to exclude the presence of a third phase.

The not condensable CO_2 -content is readily explained by assuming a rather high pressure in the inclusions at room temperature. At a pressure of, for instance, 50 kg/cm^2 and a temperature of 15° C about 2.1 mol.% CO_2 is soluble in water (fig. 31). This figure rapidly increases on lowering the temperature and it amounts to 3.1 mol.% at 0° C. Hence if any CO_2 is present in the "spherical body" this might enter on cooling into the aqueous solution, thus depleting the volatile phase of CO_2 . As a result of the entering of CO_2 into the aqueous solution the pressure within the cavity will decrease, the volume increment of the aqueous solution being smaller than the volume of CO_2 previously occupied in the "spherical body". Because of the pressure decrease less CO_2 can be solved in the aqueous solution. This means that the isochore may intersect the three-phase line, though the intersection may occur at very low temperature values, (possibly below the freezing point of the aqueous phase, Roedder, 1962) since the isochore runs almost parallel to the three phase line (fig. 30).

This reasoning leads to the conclusions that, if a CO_2 containing inclusions does not show the condensation of CO_2 within the 31° - 15° C range, it will become difficult to detect on further cooling the phase transformation because of the small quantities of CO_2 present in the volatile phase at low temperatures. As a general rule one may say that the flatter the isochore, the more difficult it is to detect CO_2 as a liquid phase.

The composition of the inclusion content can be calculated from the solubility of CO_2 in water at 40 kg/cm^2 and 15° C, (being approximately 1.8 mol.% CO_2) the density of CO_2 in the volatile phase (ranging from 0.15 gr/cm^3 to 0.05 gr/cm^3), and the ratio between the condensed and the vapour phase (generally being 4 : 1). This composition thus varies, according to fig. 30 and 31, between 2.5 and 4.5 mol. % CO_2 .

38 Homogenization temperatures

Homogenization of the old vein quartz's inclusions takes place in a rather narrow temperature range (260° - 290°), notwithstanding the large diversity of vein type and geological situation. Within one crystal the range is even narrower and homogenization temperatures do not differ more than 15° C. Apparently, they have been of uniform densities at the moment of entrapment, and have been formed in a homogeneous medium. This means that for establishing the crystallization temperatures one has to correct for pressure.

39 Homogenization pressure, and pressure and temperature at the moment of crystallization of the old vein quartz

The course of the isochore for an inclusions of a composition

of 3-4 mol.% CO₂ is given by its intersection of the three phase line (not occurring in this case), and the temperature of homogenization. For this compositional range the homogenization temperature corresponds with a pressure of about 250 kg/cm². In the event that the filling degree can accurately be estimated and the composition is known, the course of the isochore can be constructed according the extrapolated data of Khitarov (1956b).

As shown by figure 33 the course of the isochore is rather flat in their lower temperature part, such as occurs with pure water inclusions. Only towards the end of the homogenization test, when the liquid phase almost completely fills the cavity, the pressure increases sharply, and homogenization only becomes a matter of solubility of CO₂ in water. Therefore, the bubble size remains rather constant, and behaves in this respect, different from the "void of shrinkage" of pure water inclusion.

The feature that decrepitation occurs only shortly before or after homogenization (if at all) also point to a flat course of the isochore in its lower temperature part, and a steep one near the homogenization temperature.

At the moment of homogenization the isochore intersects the boundary plane at a large angle, and this explains the narrow range of homogenization temperatures. The continued steep course of the isochore means that, if the actual temperature of entrapment lies above the homogenization temperature, the actual pressure may have been very high too.

There are, indeed, indications that we are dealing with high temperature deposits. For instance, the FeS-content of sphalerite, corresponds, according to Kullerud (1953) with crystallization temperatures in the 300°-400° C range. Exsolution of bornite from chalcopyrite, and chalcopyrite from sphalerite, high silver and bismuth-contents of the galena (Schroll, 1955) all argue for a relatively high temperature paragenesis (300°-350° C).

Assuming the crystallization temperature of quartz of the older mineralization suite to have been at least in the order of 325° C, an extrapolation of the course of the isochore leads to a corresponding pressure value of 1000 kg/cm² or more.

This pressure value represents a geologically feasible figure, since this type of inclusions does not show influence attributable to differences in level of deposition. Quartz crystals found at altitudes of 400 metres have almost the same contents of fluid inclusions as those of the same suite occurring at 1200 metres elevation, although this difference corresponds with approximately 250 kg/cm² lithostatic pressure. The absence of effects that can be caused by such level difference means that the total lithostatic pressure must have been high, and 250 kg/cm² constitutes a relatively small value.

40 General crystallization conditions

In this study the inclusions have widely been used to characterize the host mineral. Especially in the case of successive quartz phases a fluid inclusion's study provides a convenient means of distinguishing the individual phases and establishing the age relations among them.

It may even be disputed of without liquid inclusions study the

successive phases of a mineral of such constant composition as quartz can be recognized, in case the individual quartz phases do not pertain to cross-cutting vein systems.

It has been noticed in the previous paragraphs that the crystallization of quartz of the old paragenetical suite occurred under conditions completely different from the young vein quartz. The common presence of stress effects (cataclasis and undulose extinction) empty inclusions and the abundance of secondary inclusions support this point of view, and help to discriminate between both quartz phases. Apparently major tectonic movements have occurred after the deposition of the old mineral suite. The mineralizing solution of the younger paragenetic suite have brought about a partial recrystallization of the older minerals and the introduction of secondary inclusions along healed fractures.

CHAPTER II X-RAY INVESTIGATIONS

1 Test for purity of analyzed ankerite samples

The analyses of ankerite have revealed that at times the ratio Ca: (Mg + Fe + Mn) is substantially different from the ideal ratio. In order to make sure that the analyzed matter solely consist of ankerite, X-ray diagrams have been prepared with a 9 cm. Debye-Scherrer camera. These showed some samples with a clear Ca-excess to be contaminated with calcite. Attempts have been made to separate ankerite from calcite by heavy liquids in the finely ground samples. Complete separation, however, failed because of the intricate texture due to mutual metasomatic replacements, which has also been observed microscopically with incident light. Especially polished sections appeared to be very useful for discriminating between carbonates. The relief after prolonged polishing enables a more positive identification to be made that is possible with transmitted light in thin sections by the refractive indices.

Thus, for evaluating the data of the chemical analyses it is necessary to know the amount of calcite present in the sample. This has been realized by comparing the intensity of the (211) reflection of calcite of the sample with those of standards of known composition. The prepared standard mixtures of ankerite and calcite contain 1, 2, 5, 10, and 15 wt. % of calcite. As little as one percent can be detected with the powder method, since the (211) reflexion is very strong.

Although the small powder camera has the advantage of giving a quick reply to the question, if there is any calcite in the analyzed sample or not, truly quantitative data on the calcite content can only be furnished by diffractometer measurements. Proportionality between the recorded peak heights and the calcite content has been noticed to occur already for concentrations between 1 and 2% calcite. For concentrations of less than 1 percent the peaks hardly reach above the fluctuations of background radiation. Sufficiently accurate measurements (relative error less than 10%) are possible with samples containing between 2 and 10 percent calcite. The higher the calcite percentage, the more close becomes the proportionality.

Thus, subtracting for admixed calcite the molecular percentages of ankerite or dolomite can be calculated.

2 The variation of lattice spacings with chemical composition of ankerites

After correction for admixed calcite and having made sure that any calcite, not corrected for, amounts to less than one percent,

there still remain quite a few analyses featuring Ca: (Mg + Fe + Mn) ratios that exceed considerably the ideal value. Apparently, next to the commonly recorded Mg - Fe - Mn substitution each of these elements may also be replaced by calcium or conversely. The common Ca-excess of ankerite analyses is recorded by Smythe and Dunham (1947), but the purity of their samples has not roentgenographically been checked.

Since the author disposed of a set of ankerite analyses and corresponding X-ray diffractometer recordings, covering a large field of chemical compositions, it appeared interesting to investigate the effects of both types of substitution on the unit cell constants. As yet this has not been done and it might lead to a ready approximation of the chemical composition. 1)

The crystallography of the series of calcite-dolomite-magnesite solid solutions and many other rhombohedral carbonates, whether artificially or naturally grown, has been investigated by Goldsmith, Graf and Heard (1955 - 1962), and leaves little to be added. The variation of the a_0 and c_0 cell constants and the (211) lattice spacing of the calcite-dolomite solid solution series is represented by fig. 34. This diagram is designed according to Graf's data. In this diagram, however, only Ca-Mg substitution is drawn into consideration. The simultaneous presence of Ca-Mg-Fe-Mn substitution renders the effect on the cell constants more complicated. Replacement of Mg by Ca or Fe will increase the cell constants. The effects of calcium are predominant over iron, calcium having the greatest ion radius.

As parameter of the unit cell constants the value of the (211) lattice spacing has been chosen, since its value, making use of the available diffractometer (Hilger) could be determined with sufficient accuracy to compare the author's result with those of Graf. The value of the (211) reflection has been calculated as average of (211), (422) and (633) spacings. For the (422) and (633) spacings there has been made use both of $Cu\alpha_1$ and $Cu\alpha_2$ radiation. Scanning occurred in both directions (for increasing and decreasing reflection angles).

The diffractometer has been calibrated against quartz and halite. A correction graph has been plotted for either sense of rotation of the counter tube.

The low intensity of the (633) reflection (congruent with the (522) reflection) did require the employ of pure samples for preventing possibly interfering reflections, since the (633) reflection is only difficultly detected because of its low intensity. Fine grinding (to minus 325 mesh) and subsequent treatment with heavy liquids did remove most impurities. X-ray diagrams still featuring reflections other than those of ankerite have been discarded.

Although relative errors in determining the (211) lattice spacings have thus been reduced, instrumental errors affecting the absolute values remain. In order to check the author's result with those of Graf a clear dolomite crystal proving

1) A recent study of Goldsmith, Graf et al. (1962) containing data on the unit-cell dimensions of the ankerite-dolomite solid solution series has been noticed too late by the author to be drawn into consideration here. The present author's results, however, may still be of interest, since they extend to ankerites with a Ca-deficit.

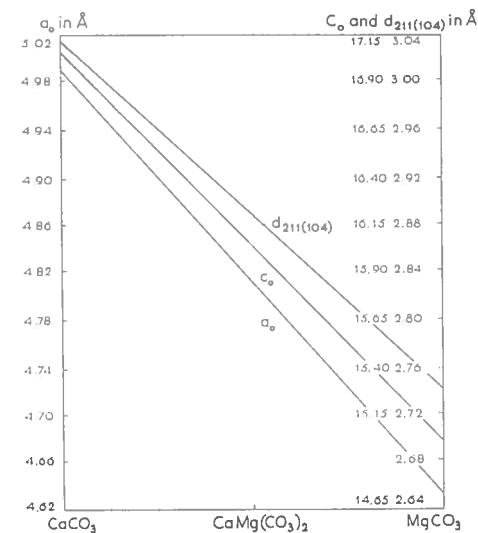


Fig. 34. Variation of unit cell dimensions, and the {211} lattice spacing of dolomite of a hypothetical calcite and magnesite solid solution series, according to Goldsmith and Graf(1958).

from the same (famous) locality (Binnental - Switzerland) has been investigated. The author's value of the (211) lattice spacing as calculated from the (633) reflection is 2.8842 Å, and differs slightly from Graf's value: 2.8857 Å, but fits into the range of d-values of almost ideal dolomites, being situated between 2.8842 Å and 2.8857 Å. The calcium content of these dolomites varies between 49.55 and 50.76 mol.% CaCO₃.

The values for the (211) lattice spacings are plotted in a diagram representing the chemical composition as solid solutions of Ca Ca (CO₃)₂; Ca Fe(CO₃)₂ and Mg Fe (CO₃)₂ (fig. 35). In order to make the diagram not too complicated the iron and manganese equivalents have been combined. This induces, however, an error in the representation of the lattice spacings as function of Ca: (Mg + Fe) and Mg : Fe substitution, since the ion-radius of bivalent manganese and iron differ more than those of iron and magnesium.

It appears from the diagram that the effects of Ca-substitution are predominant over all other substitution types. Moreover, it should be noted that the Fe- and Ca-rich ankerites only difficultly fit into the scheme, which may be due to the high Mn-content of these ankerites. Possibly this is a reflection of the feature that Ca and Mn completely substitute for each other in the calcite structure. The specific gravity values are taken from Smythe and Dunham (1947). Combined with the lattice spacing they enable an estimation of the chemical composition of the ankerites to be made, since both parameters intersect each other at high angles.

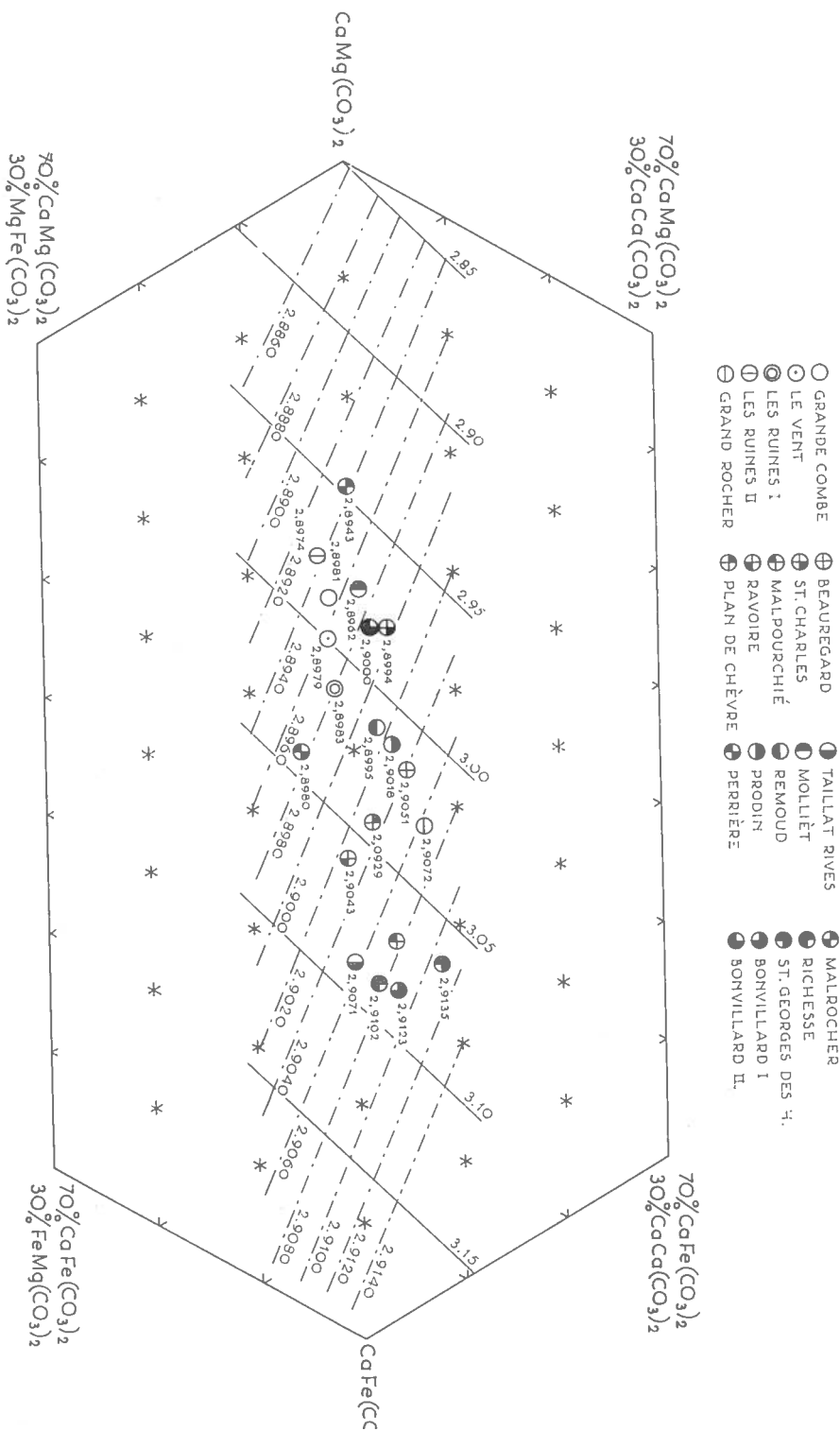


Fig. 35. Variation of specific gravity and (211) lattice spacings of dolomite and ankerite.

CHAPTER III

THE CHEMICAL ANALYSES

1 Purposes of the analyses

Since the ore deposits of the Belledone are of a rather uniform type, one of the first questions to arise during this study was, whether there is any significant difference in chemical composition of the individual minerals. An indication in this direction is given by siderite. This mineral is recorded by Gueymard (1844) to occur in two types one consisting of coarse grained siderite, called Maillat and an other fine grained typed called Rives. Gueymard has shown this textural distinction to have chemical significance, too. The Maillat siderite was said to contain more magnesium and less manganese than the Rives siderite.

2 The siderite analyses

The present analyses have fully confirmed the existence of two chemically definable types of siderite, but the data of Gueymard are not accurate enough to be used for a geochemical study.

Since siderite occurs in almost all veins and in widely diverging parageneses, its composition is assumed to reflect several stages of ore deposition. For these reasons it has become desirable to dispose of analyses of all siderite occurrences. The execution, however, of a hundred and sixty analyses according to standard methods means a rather time consuming affair. Therefore a special method of analyzing siderite has been developed.

3 Preparation of the sample solution

The constituents to be determined comprise ferrous- and ferric iron, manganese, magnesium, calcium, titanium, carbon dioxide and water. For the determination of total iron, manganese, magnesium and calcium a 0,5 gram sample is dissolved in hydrochloric acid. After carbon dioxide production has ceased, hydrogen peroxide is added in order to oxidize ferrous iron into the trivalent state and manganese into the quadrivalent state. Bivalent manganese interferes when preparing the solution from which calcium and magnesium will be determined. Bromine water also being a potent oxidizing agent, may be used instead of hydrogen peroxide.

Large amounts of hydrogen chloride interfere with the manganese determination, and hydrogen peroxide interferes with the Ca and Mg titration. Hence, after solution is completed both must be removed by complete evaporation, which also serves to

precipitate possibly dissolved SiO_2 . The residue is taken into solution with diluted nitric acid, filtered by a porcelain filter and transferred into a 250 ml. volumetric flask. The water necessary to make up to volume is used to rinse the residue out of the Erlenmeyer. The residue, consisting of quartz and country rock fragments, is weighed after drying the porcelain filter.

4 Colorimetric analyses of total iron

Several methods of colorimetric iron determination have been tried, before it was decided to use the salicylic acid methods. The iron-salicylic complex develops its amethyst colour only at relative high iron concentrations (0.1 - 3.0 mg. ferric iron per ml.), which means a decided advantage for iron ore analyses. Moreover, by means of various standard solutions the system has been shown to follow Beer's law over a wide range of concentrations (50 - 2 ppm in the final solution) with an accuracy of about 0,1 percent. In order to reach these concentrations only 5 ml. of the sample solution should be taken, which implies careful pipetting preferably with Desicote coated pipet. Since even the slightest error may affect the final accuracy of the analysis, iron being the major constituent, a correction graph has been plotted.

The color intensity is susceptible to Ph-variations. Therefore a rigid control over the Ph of the final solution is necessary since the colorimetric results are to be multiplied by fifty. This has been achieved by adding an ammonium-acetate-acetic acid buffer solution after the addition of the 10 ml. 1 percent sodium-salicylate solution. The buffer solution should keep the Ph at 2.6 a value for which maximum color intensity is attained. Having made up to 100 ml. the color is measured at 530 milli- μ .

5 Colorimetric analysis of manganese

The generally applied method of colorimetric determination of manganese by oxidation to permanganate in a strong sulphuric acid solution, is also the most suitable for siderite analyses. A 25 ml. aliquot of the sample solution is treated with sulphuric acid, periodate and phosphoric acid (decolorizing iron), and made up to 100 ml. It gives a permanganate coloration of such intensity that the Beer's law is followed for siderites containing 0,5-10 wt. % manganese.

6 Volumetric calcium and magnesium determinations

Titration with di-sodium-ethylene-diamine tetra-acetate (sodium-versenate) provides a simple and quick method for determination of Ca and Mg, elements that form complexes with versenate (Schwarzenbach, 1954). The end of the titration is marked by a color change of a suitable indicator.

Iron and manganese, however, interfere with the determination and must be removed. This is most readily done by precipitation as hydroxide, which occurs at a Ph of 5. Since magnesium also

tends to precipitate at high Ph-values, and the precipitate of iron-hydroxide tends to occlude Mg- and Ca-ions at high Ph-values, care has to be taken with the addition of the neutralizing ammonium hydroxide. Control with a Ph-meter is desirable. Boiling the solution will give a coarser, and easier to filter precipitate.

The titration gains in accuracy if relatively large amounts of Ca or Mg are present. Hence, a 100 ml. aliquot should be taken from the sample solution for treatment with ammonium hydroxide. After filtering off the precipitate the solution is cooled and brought to 250 ml.

Ca and Mg react equally with versenate. For determining Mg, calcium has to be removed. Ca is precipitated as Ca-tungstate in an alkaline environment. To make sure that precipitation starts a slight amount of CaCl_2 is added in advance. The precipitation should occur in the presence of ammonium salts (1 gr. NH_4Cl and 5 ml. concentrated NH_4OH) in order to prevent Mg from being precipitated alongside as Mg-hydroxide. Several control analyses of standard solutions have shown the precipitation of Ca to be quantitative, whereas excessive amounts of Ca-tungstate did not affect the accuracy of the Mg-titration.

The Mg-titration with versenate does not require the Ca-precipitate to be filtered off, but the Ph has to be 10.0. In this environment murexine (ammonium-purpurate) is a suitable indicator.

The sole objection to this method is the difficulty in observing the colour change at the end of the titration. The color change takes place from red, over violet, indigo-violet, corn-flower-blue to greenish-blue. The colour change between indigo-blue and corn-flower-blue is most sensitive. An artificial colour standard has been prepared, and the versenate solution has been standardized for this colour change.

The removal of Ca from the solution to be titrated for Ca is simple. The addition of 10 ml. 15% sodium-hydroxide suffices for precipitating Mg as magnesium-hydroxide. Tests with solutions of known Ca- and Mg-concentrations, however, have shown the Mg-precipitate to occlude Ca-ions. Therefore the versenate-solution has been standardized for several Mg : Ca ratio's. Eriochroom-black-T is used as an indicator.

The colour change is easily observable but may fail to develop completely in the presence of appreciable amounts of manganese-hydroxide. In this case manganese has to be removed from the sample solution after precipitation of iron by treating the neutralized solution with bromine water, which precipitates manganese as manganese dioxide.

7 Colorimetric determination of titanium

The determination of traces of titanium in the presence of excessive amounts of iron implies a special analytical method to be used. With the normal procedure of coloration with hydrogen peroxide iron has to be removed, moreover the colour is too faint to be detected in concentration of less than 2 ppm of the final solution. The coloration with thymol is about 25 times as intense as that produced by the hydrogen peroxide method. Thus detection of titanium in a concentration of 0.05 ppm is possible

(Lehner and Crawford, 1913).

A fortunate coincidence is that the coloration is optimal in concentrated sulphuric acid, in which titanium dioxide is readily soluble. Although iron does not produce any coloured complex with thymol, the coloured iron sulphates may still interfere.

This problem is overcome by prohibiting the major part of the iron to enter into the sample solution. This has been achieved by heating the sample in a crucible to convert iron carbonate or hydroxide into Fe_2O_3 and Fe_3O_4 , iron compounds that are insoluble in a mixture of ammonium sulphate and concentrated sulphuric acid, whereas the author's experiments have shown TiO_2 to be readily soluble in this solution mixture.

After cooling the sample solution is decanted into a 50 ml. volumetric flask; thereupon 5 ml. solution of 1% thymol in acetic acid is added. The solution is brought to volume with concentrated sulphuric acid.

Care should be taken when adding the sulphuric acid in order to prevent desintegration of thymol by heat.

The reddish solution is compared at 470 milli- μ with a standard and a blank, both equally treated with the fusion mixture and iron oxides.

8 Acidimetric CO_2 -determination

The commonly practiced gravimetric way of determining CO_2 quantitatively is a rather cumbersome affair. Although the CO_2 -content does not provide any information of geochemical interest about siderite, yet omitting the CO_2 analysis is not desirable because of the lack of check on sum total and precision of the analysis.

The acidimetric method of treating the sample with a known amount of acid and, back titration of the solution to neutrality after carbon dioxide production has ceased, gives satisfactory results for the present purpose.

5 ml. 10 N H_2SO_4 has been used to dissolve a 0.5 gram sample and a 1.0 N NaOH-solution for titrating to a Ph of 7. Before titration 10 ml. of a 25% solution of sodium-tartrate has to be added for removing iron as a complex bond, which otherwise will precipitate as hydroxide.

The major objection against this method concerns the reaction of the acid with other compounds than carbonates. Notwithstanding the dilute nature of the acid used and the slow attack of sulphuric acid to iron hydroxides or oxides, as compared with nitric or hydrochloric acid it is still inevitable that some oxidic or hydroxidic iron compounds go into solution. This means that not all acid used by the solution process of siderite may be credited to the carbon dioxide content.

The presence of iron compounds as oxides and hydroxides with the siderite is the result of alteration, a process by which Ca and Mg from readily soluble compounds and are leached away. The remaining iron is oxidized into the trivalent state and forms hydroxides such as goethite and lepidocrocite.

Analyses on siderite or ankerite occurring in this stage of alteration give doubtful CO_2 -values, since these hydroxides are better soluble than the iron-oxides that normally occur with

siderate in an advanced stage of alteration. A determination of ferric and ferrous iron content makes us aware how far alteration has proceeded in the sample investigated. An analysis of the water content, too, may help to establish the degree of alteration. The water content is proportional to the amount of iron-hydroxides, and thus gives information to which degree the CO₂-values are erroneous.

Both ferrous iron and the water-content have to be determined for completion of the analysis.

9 The volumetric ferrous iron determination

The solution serving for the CO₂ analysis may also be used for the determination of ferrous iron, since ferrous-sulphate is stable in sulphuric acid solution. An aliquot taken from this solution is titrated with potassium-dichromate.

10 Gravimetric determination of water and correction of CO₂ content

After drying the sample in air of 25° the total water-content, (whether adherent moisture or chemically bound) has been determined by the Penfield-method.

Using the data of the water analysis and the ratio ferrous: ferric iron one is able to check the CO₂-content determined, with the quantity of CO₂ that should be present, if all bivalent irons are calculated as carbonate cations. It then appears, that even in the case of completely unaltered carbonates there always exist a CO₂-deficit, notwithstanding the fact that the analyses under question are believed to be absolutely correct, and the total weight percentages equal a hundred. Moreover, the ferric iron content of such unaltered siderites does not correspond with the water content if the ferric irons are seen as products of an incipient alteration.

As mentioned above, analyses of altered material will fail to show the CO₂-deficit, if the total amount of acid consumed by the solution process is calculated as being due to CO₂ solely. A correction factor may be derived from the amount of hydroxides that is likely to be present according to the water-content. The author's experiments have shown that about 30 percent ($\pm 5\%$) of the ferric-hydroxides pass into the dilute sulphuric acid solution. Thus, its equivalent has to be subtracted from the total acid consumption.

11 Determination of Ti in hematite, magnetite and ilmenite

The determination of titanium, occurring as trace-element in hematite or magnetite or as main constituent in ilmenite, has been performed in the same manner as with the carbonates. Calcination of the sample however, is not necessary. About the accuracy of the thymol method it is rather surprising to note that an analysis of ilmenite of Chalanches shows a molar ratio Fe : Ti or 1.01 : 1.

12 Analysis of sphalerites

The variation of chemical composition of sphalerite mode of occurrence or temperature of deposition have been extensively investigated (Schroll, 1955, and Kullerud, 1953). A few spectrochemical analyses and the Fe-content (as reflected by the colour) indicate that the sphalerites of the Belledone have crystallized under widely diverging conditions, and justifies an analyses of the minor constituents. The analytical methods used do not represent any special technique; and therefore, will only briefly be mentioned.

a. Copper

After solution of a 0.5 gr. sample in concentrated HCl + HNO₃, and evaporation of both acids with concentrated H₂SO₄ until fumes of SO₂ are given off, the sample solution is treated with NH₄OH until Zn(OH)₂ goes into solution. The precipitates of iron and manganese are filtered and washed with diluted NH₄OH. The blue colour of the cupric-ammonia-complex is compared with standards.

b. Iron

The combined iron-manganese precipitates are dissolved in dilute sulphuric acid. An aliquot is taken for the determination of total iron according to the salicylic method. In the case of iron rich sphalerites, the so called marmatites, the iron-content in the final solution must be diluted in order to prevent a concentration of over 6 mgr. per 100 ml. Above this concentration deviations from Beer's law have been noted. The molar ratio ZnS : FeS is calculated from the total iron content minus the amount of iron necessary to form chalcopyrite with copper. The FeS-content provides information about the crystallization temperature (Kullerud, 1953).

c. Manganese

An aliquot of the solution prepared from the acid dissolved hydroxides is used for the colorimetric determination of manganese by the permanganate method. If the precipitation of manganese with iron-hydroxides at a Ph below 7 is not complete, it has to be oxidized into the quadrivalent state by boiling with bromine solution.

d. Cobalt and nickel

Cobalt and nickel are readily determined by chromatographical methods. The sample solution is prepared by solving a 0.9 gram sample in concentrated nitric and hydrochloric acid. This solution is evaporated and taken into solution by 1 ml. 1 : 1 HCl. Drops of 0.01 ml. are brought by a small pipet on chromatographic paper strips. These are, together with standard treated strips, placed in a solvent consisting of 87 vol. % acetone, 8% 12 N HCl, 5% water or 90% methyl-ethyl-ketone, 5% concentrated HCl and 5% water (data according to: Pollard and

Mc. Omie, 1953). The Rf values for the various elements are: Ni : 0,05; Co : 0,5; Cu : 0,65; Zn : 0,9. Iron migrates in the solvent's water front. After neutralizing over NH_4OH vapours and drying (air dry), the strips are sprayed with an alcoholic solution of 0.1% rubeanic acid, which forms coloured metal compounds: pale blue with nickel, brown with cobalt and green with copper. The dimensions and intensities of the coloured spots are compared against standards.

e. Cadmium

Cadmium equally is determined chromatographically making use of the same sample solution. The solvent used consists of 50 vol. % butanol and 50 vol. % hydrochloric acid (Pollard and Mc Omie, 1953). It is one of the few solvents that are capable to produce at least a partial separation of Zn and Cd. The Rf-value for Zn is 0,51, for Cd : 0,37. After the alcohol front has reached the end of the strip, the paper is dried and sprayed with an alcoholic solution of 0.02 % Cadion (p-nitrodiazo-aminobenzene) 0.02 N potassium-hydroxide and 0.1% sodium-potassium-tartrate (for tying up iron). Cadmium-ions develop an orange-red coloured spot with the reagent solution. The overwhelming amounts of zinc, which tends to "tail" in the chromatogram, may inhibit the development of a definite Cd-spot.

13 Analyses of galena and tetrahedrite

A chromatographic estimation of the silver content of galena and tetrahedrite from an ammoniacal sample solution, using a solvent mixture of 60% butanol, 4 vol. % pyridine and 36 vol. % water (Rf Ag = 0.5) and p-dimethylaminobenzal-rhodamine as reagent, did only produce rather vague spots and proved to be not accurate enough for a geochemical investigation for silver. Actually, the silver assay values as performed by Holl. Metallur. Bedrijven in Arnhem (Netherlands) are so close to each other (and close to those of Gueymard, 1844) that any discrimination among them can hardly be expected to be produced by chromatography (Part II).

The copper content of galena has been determined in the same way as with sphalerite, using an ammoniacal extract of the dried acid treated sample.

Bismuth has spectrographically been determined by the H.B.M. in Arnhem. An error of about 5% relative is possible.

14 Analyses of chlorite and stilpnomelane

The determinations of the elements likely to be present in chlorite and stilpnomelane were made accordingly to the analytical way commonly used for silicate analyses by the Petrochemical Laboratory of the Depart. of Petrology and Mineralogy of the Leiden University, (under the direction of Dr. C.M. de Sitter-Koomans). The methods involve mainly colorimetric and volumetric techniques as recommended by Shapiro and Brannock (1952).

PART II MINERALOGY

In this part a brief review will be given of all ore vein minerals of the Belledonne, so far as observed by the author.

1 Adularia

Euhedral adularia crystals occur in vugs at high altitudes in the Bonvillard mining lease (nr. 108). Adularia is accompanied by galena, chlorite and clear crystals of quartz. The quartz crystals feature water-filled primary inclusions of 180° homogenization temperature. The assemblage suggests a mineral paragenesis of Alpine age. Adularia belongs to the common Alpina vugh minerals (Parker, 1940).

2 Albite

Albite is of widespread occurrence in the Belledonne Massif. Albite porphyroblasts mark the Outer Zone schists. They are characterized by trains of minute rutile needles denoting the old micro-folding. This type is absent in the Inner Zone, where albite occurs as retrograde metamorphic alteration products of plagioclase, or as young porphyroblasts related to recrystallization or metasomatism of Alpine age (Tobi, 1959, Kalsbeek, 1962). The latter type is also met in the Palaeozoic and Mesozoic sedimentary cover, and is accompanied by albite impregnations and veinlets. Thus it gives evidence for redistribution of material during Alpine orogeny.

3 Allemontite

The ore deposit of Chalanches situated near the village of Allemont is the type locality of allemontite. The earliest mention of allemontite is from le Sage (1777), who has described it as "pyrite arsenical à facettes hexagonal". Romé de l'Isle (1783) has recognized the mineral to be a natif element. Hauy (1801) named the substance "antimoine natif arsénifère". Haidinger (1843) proposed the name allemontite. Rammelsberg (1844) analyzed the mineral (Sb: 37.85 %, As: 62.15 %). Hörnes (1846) described allemontite as accompanied by native antimony and arsenic. Van der Veen (1925) is the first author to give a mineralogical description of allemontite. He proposed to drop the name allemontite as a mineral species and only to make use of it to designate the eutectoid fabric between arsenic and antimony. Wretblad (1941), however, demonstrated the existence of solid solutions of antimony and arsenic of a fixed composition: AsSb and observed the allemontites investigated by him to be composed of Sb and AsSb (allemontite I) or pure AsSb (allemontite II) or As

and AsSb (allemontite III). The former two associations occur at Chalanches, which appears from Wretblad's analysis mentioning a Sb + AsSb intergrown mixture: 36 % As and 62.2 % Sb.

Allemontite is easily recognized because of its graphic intergrowths with antimony or arsenic, and the black tarnish that arsenic gets upon exposure to air.

Allemontite is said (Gueymard, 1844; Chabrand, 1913) to belong to the suite of Co-Ni-minerals of Chalanches and differs in this aspect not from other identical parageneses (Freiberg, according to Baumann, 1959; St. Andreasberg, according to Stelzner-Bergeat, 1906). Its exact position in the paragenetical sequence has been established only with regard to silver I (which is older) and pyrrargyrite (which is younger).

4 Anatase (Octahedrite)

Anatase, like adularia, it is typical Alpine vugh mineral (Parker, 1940) and has been noticed to occur in quartz-chlorite veinlets near Fond de France.

5 Anglesite

The presence of anglesite may be assumed in all altered lead-zinc deposits, but it could only be ascertained in the Richesse deposit where the alteration zone of the ore body has only partly been mined. In most deposits the gossan has been the first part to be exploited. Many interesting supergene products occur in the Richesse veins.

6 Ankerite

Ankerite ranks with siderite, galena and sphalerite among the Belledonne's main vein minerals. It is present in several types of veins or parageneses, and occurs both in Inner and Outer Zones. Generally, ankerite is a replacement product of siderite by Ca-bearing solutions. Its chemistry may essentially have been modified by recrystallization.

All ankerite occurrences have been analyzed. The samples have been checked for purity by X-ray powder methods. Where the X-ray diagram has shown the presence of calcite, which is difficult to separate from ankerite because of intricate intergrowths, the quantity of the contamination has been estimated from the peak height of a recorded diffractometer diagram, and has accordingly been subtracted.

The analyses have been made with the aim of investigating a possible relation between chemical composition and the type of process that has led to the deposition of ankerite. The composition of ankerite is represented in fig. 36, as solid solution of CaCO_3 - $\text{CaMg}(\text{CO}_3)_2$ - $\text{CaFe}(\text{CO}_3)_2$ and $(\text{Mg, Fe})\text{CO}_3$.

It appears from the diagram that distinct groups can be discerned.

Group I

The ankerites of this group are characterized by high iron and

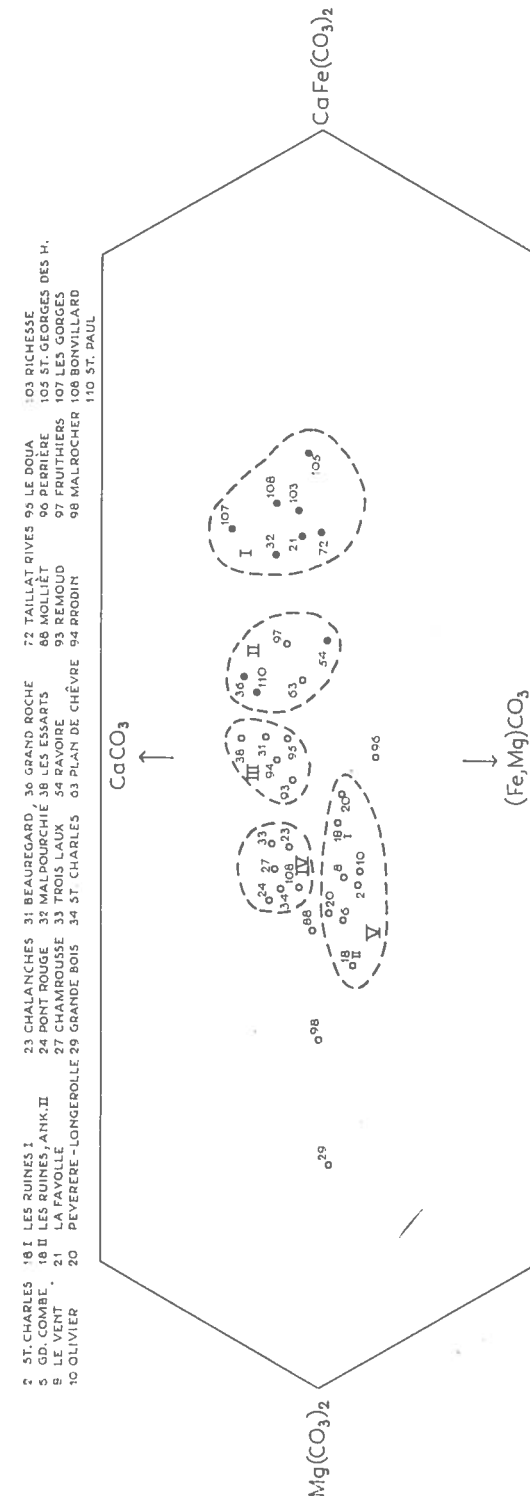


Fig. 36. Variation of chemical composition of ankerite, representing the 5 genetical groups.

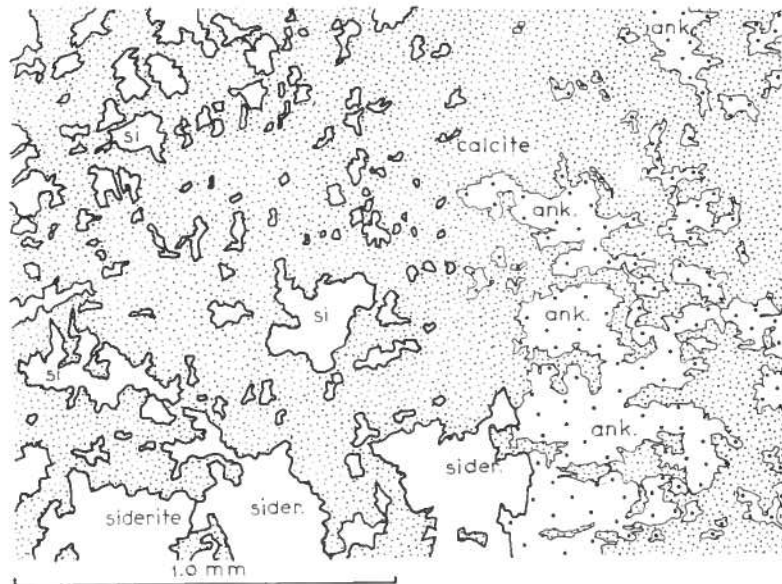


Fig. 37. Siderite and ankerite (ank.) replaced by calcite, Malpourchié.

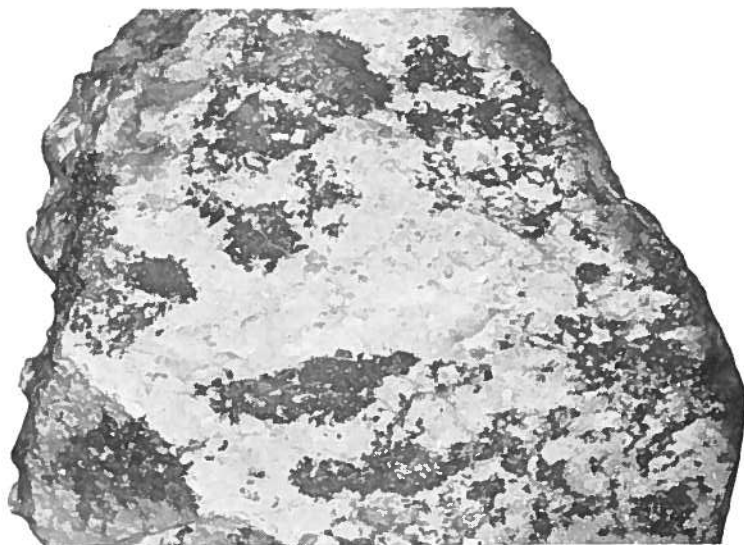


Fig. 38. Age relations between siderite and ankerite appears from replacement of siderite (dark gray) by ankerite (light gray). Note the arbitrarily shaped replacement relics. Les Gorges, 1 x.

manganese content, and an intricately intergrown fabric of highly strained crystals. The black dots of the figure refer to this type of fabric. They all are replacement products of siderite.

The character of the replacing solution is particularly clear with the Malpourchié vein (nr. 32) where ankerite occurs as an intermediate stage between siderite and calcite, fig. 37. The chemical mechanism of this replacement appears from a comparison of siderite and ankerite analyses. The replacement proceeds by incorporation of all magnesium available into the dolomite structure and an additional filling of the remaining magnesium sites by iron and manganese in about the same ratio as present in siderite. There is marked tendency to incorporate more manganese, rather than iron, especially when Ca occurs in excess of other bivalent cations, which feature may hold an explanation for the discrepancy between the high experimental temperatures required for the formation of highly ferroan ankerite in an environment free of manganese, and the generally accepted natural crystallization temperatures (Goldsmith et al. 1962).

Ankerites pertaining to this group are of widespread occurrence and can be met in the Inner Zone (Malpourchié, 32), or in the Outer Zone. In the latter part the occurrences are less common in the part west of the Carboniferous syncline of Mont Jean and Grand Collet (Taillat Rives, 72) than they are in the eastern part of the Outer Zone, where they are found the extreme North: Richesse, (103), St. Georges des H. (105), Bonvillard (108) and Les Gorges (107) and in the southern most area: La Fayette (21). Figure 38 shows the replacement of siderite by ankerite. As shown by fig. 39, not all ankerites are replacement products, veins may also occur. The fabric and composition of this group indicate that recrystallization is not likely to have occurred with these ankerites.

The paragenesis of this group is a high-temperature one, irrespective of the situation of the deposit. The ankerites are accompanied by Co-Ni-sulphides and black sphalerite, containing essential amounts of chalcopyrite in solid solution (> 1%). It is interesting to note that the experiments of Rosenberg (1959) on the solid solubility of Ca, Mg and Fe-carbonates in the 350-550° temperature range agree with the chemical analyses of ankerites of group I, since the high-ferroan ankerites (the highest possible iron-content in the presence of siderite and calcite) are met only in parageneses for which a high temperature is likely.

Group II

The ankerites of this group cannot clearly be distinguished from those of the first group. They occur in the same environment and in the same paragenesis and only differ from the first type by the degree of strain showing less frequently disruption and "wavy" extinction. In most instances a partial recrystallization can be observed, but this has been an almost isochemical process, since the chemical differences within this group are small.

Group III

Not all ankerites are genetically related with siderite. There

are also examples for which the origin is not known, such as the young ankerite of Malrocher (no. 98). These late mineralization phases have often accomplished a partial recrystallization of the old vein content. Old ankerites or siderites may also have been incorporated into the younger solution and have led to ankerites of a composition intermediate between that of the old vein content (group I) and that of the younger ankerite (no. 98). The composition of group III has to be seen in this light, and this also means a feasible solution to the question why the ankerites of Remoud, Prodin and Le Doua have a composition different from that of Malrocher, although all are of the same phase.

Group IV

The composition of the ankerites of this group is intermediate between those affiliated with siderite (group I and II) and a carbonate of almost dolomite composition from the Grand Bois deposit (nr. 29), from which follows that this group is confined to the Inner Zone (Allemont area). The origin is believed to be of the same nature as that proposed for group III. The compositional range, however, is larger and extends to group II. This is due to variable quantities of old carbonates incorporated into the dolomite solution, or conversely, to the incorporation of dolomite into siderite-bearing solutions. In the case of limited amounts of older siderite or ankerite being available, these may even be absorbed completely as with the Chalanches (23), Pont Rouge (24), and Chamrousse (27) deposits, or they have been reduced to small relics as with Beaugard (31), Trois Laux (33) and St. Charles (34) as shown by figure 37.

In this type replacement occurred in such an intricate manner as to make both components difficult to be separated (fig. 40). The crystallography of the quest is oriented upon the host mineral. Care should be taken with the interpretation of such replacement phenomena, since both minerals may belong to the same mineralization phase, or in the case of different ages, the younger one (calcite) may attack the older one (ankerite) firstly in its center, and thus an innermost situated mineral not necessarily should be interpreted as an older replacement relic (St. Charles, fig. 40).

Group V

Ankerites belonging to this group exclusively occur in the Belledonne's Outer Zone, west of the Carboniferous Syncline of Mont Jean (Vizille area). They are distinguished by their Ca-deficit and low manganese and iron content, a feature that is in agreement with their mode of origin, being replacement products of siderites with low manganese and high magnesium contents. In contrast to the siderite-ankerite-calcite series of the Inner Zone and the eastern part of the Outer Zone, no deposition of calcite took place here after the crystallization of ankerite, which explains the Ca-deficit. As with the ankerites of group I, this group also displays a close relationship between the magnesium contents of siderite and ankerite, both having equal molecular percentages.

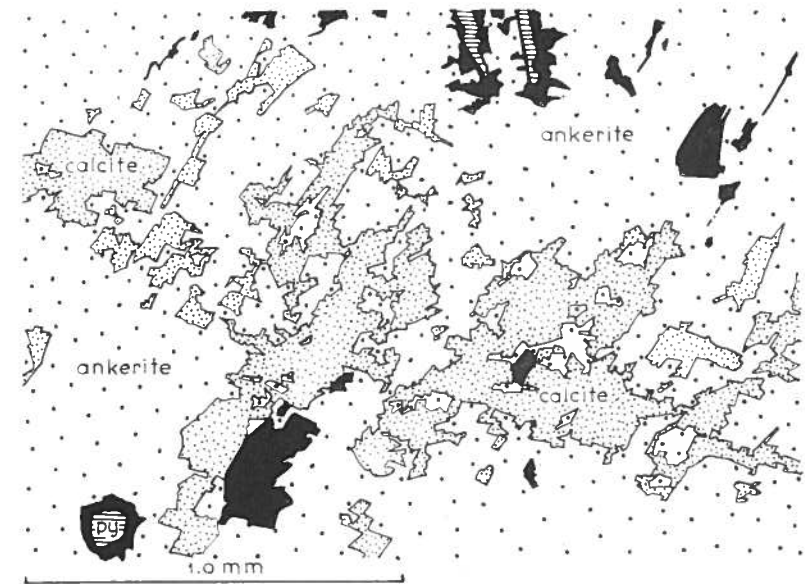


Fig. 39. Replacement of ankerite by calcite starts in the centres of the ankerite crystals, thus pretending the calcite being a replacement relic. Calcite is crystallographically oriented upon ankerite. St. Charles, Allemont.

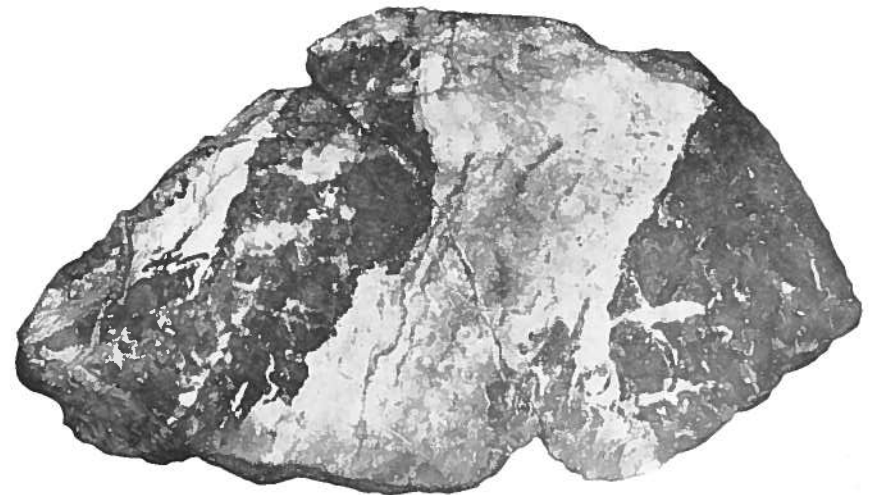


Fig. 40. Veins and veinlets of ankerite dissect siderite (dark gray). Les Fruithiers, 1 x.



Fig. 41. Large rhombohedral crystals of ankerite. Found in vugs of the Grande Combe vein, $\frac{2}{3}$ x.

	2 ST. CHARLES ankerite	6 GRANDE COMBE ankerite	8 LE VENT ankerite	10 OLIVER ankerite	18 LES RUINES ankerite II	18 LES RUINES ankerite I	20 PEYERERE ankerite
FeO	14.51	13.57	14.75	13.99	8.56	11.98	15.32
MnO	0.48	0.24	0.35	0.38	0.40	0.44	0.19
MgO	12.29	13.04	12.47	11.50	9.72	8.56	9.70
CaO	26.78	27.78	27.85	26.00	19.24	21.00	24.54
Fe ₂ O ₃	0.73	0.96	0.64	0.76	1.26	0.15	0.25
CO ₂	42.16	40.66	43.10	39.92	30.10	32.56	37.50
H ₂ O	1.76	0.76	0.81	1.77	0.58	0.94	1.00
res.	0.72	2.48	0.73	5.48	30.48	24.70	11.92
	99.43	99.49	100.70	99.80	100.34	100.33	100.42

	20 PEYERERE ankerite	20 LONGEROLLE ankerite	21 LA FAYOLLE ankerite 20% siderite	23 CHALANCHES ankerite 10% calcite	24 PONT ROUGE ankerite 25% calcite	27 CHAMROUSSE 50% ankerite 6% calcite	31 BEAUREGARD 91% ankerite 3.5% calcite
FeO	14.04	8.28	23.84	12.20	8.44	6.77	13.83
MnO	0.12	0.14	1.48	1.84	2.07	0.77	2.32
MgO	9.56	7.91	7.40	10.50	9.48	6.25	8.40
CaO	23.64	17.20	21.70	30.20	31.50	18.58	27.90
Fe ₂ O ₃	—	0.14	2.76	1.64	5.14	1.56	2.35
CO ₂	36.18	26.64	40.62	39.20	39.10	25.52	38.30
H ₂ O	0.97	1.09	0.79	1.57	1.62	0.92	1.19
res.	14.44	37.84	1.02	2.18	2.26	40.00	4.78
	99.96	99.24	99.61	99.33	99.61	100.37	99.07

	32 MALPOURCHIE ankerite	33 TROIS LAUX 65% ankerite 15% calcite	34 ST. CHARLES 90% ankerite 4% calcite	36 GRANDE ROCHE 80% ankerite 7% calcite	38 LES ESSARTS 95% ankerite 5% calcite	54 RAVOIRE ankerite	63 PL. DE CHÈVRES ankerite
FeO	17.68	12.80	12.20	12.82	12.73	16.26	18.24
MnO	3.09	2.04	1.29	3.44	2.45	0.89	0.52
MgO	8.40	4.25	11.62	6.88	7.92	6.62	8.14
CaO	26.40	25.50	29.60	28.44	29.52	22.30	26.78
Fe ₂ O ₃	5.98	3.26	1.36	2.92	2.52	1.52	0.92
CO ₂	36.88	31.20	42.21	37.84	41.04	35.34	40.82
H ₂ O	3.16	1.57	0.87	0.68	2.28	1.16	1.33
res.	1.36	18.82	0.06	6.54	0.74	16.44	2.52
	100.31	99.46	99.21	99.56	99.20	100.53	99.27

	72 TAILLAT RIVES ankerite	81 GRODET ankerite 5% calcite	83 VAUJALAZ ankerite	92 ST. HUGON ankerite	93 REMOUD 90% ankerite 2% calcite	94 PRODIN ankerite	95 LE DOUA ankerite
FeO	21.00	3.51	12.24	23.64	15.20	11.54	14.24
MnO	1.77	0.22	0.22	1.44	0.58	0.58	0.46
MgO	5.98	4.72	6.58	9.54	9.79	6.87	8.70
CaO	26.04	11.16	15.74	19.46	28.20	20.56	25.02
Fe ₂ O ₃	2.23	4.66	1.34	3.00	2.16	2.75	2.22
CO ₂	38.70	15.86	27.04	39.80	40.46	29.02	37.38
H ₂ O	1.09	1.01	2.00	1.94	1.11	1.33	1.58
res.	2.34	58.60	34.20	0.98	1.74	26.50	9.59
	99.15	99.74	99.36	99.80	99.24	99.15	98.99

	96 PERRIERE ankerite 1% calcite	97 LES FRUITHIERS ankerite	98 MALROCHER ankerite	103 RICHELLE ankerite	105 ST. GEORGES D. H. ankerite	105 ST. GEORGES D. H. ankerite and goethite	107 LES GORGES ankerite
FeO	14.34	15.52	8.62	16.12	17.40	15.36	14.84
MnO	0.73	2.12	0.46	2.00	5.40	5.16	2.21
MgO	8.35	6.84	13.74	4.28	4.39	3.82	4.15
CaO	21.36	25.10	26.20	20.96	24.84	24.40	23.18
Fe ₂ O ₃	0.84	2.40	1.04	3.04	9.21	11.78	0.20
CO ₂	33.88	34.80	39.76	32.38	36.08	32.80	31.42
H ₂ O	1.46	1.62	1.48	0.27	1.80	2.90	0.31
res.	18.24	12.56	7.98	21.50	1.14	3.88	23.30
	99.20	100.96	99.28	100.55	100.26	100.10	99.61

	107 LES GORGES ankerite 10% siderite	108 BONVILLARD ankerite I	108 BONVILLARD ankerite II	110 ST. PAUL ankerite	110 ST. PAUL 95% ankerite 2% calcite	88 MOLLLET ankerite
FeO	22.84	20.20	13.20	16.26	16.39	11.74
MnO	2.75	2.94	0.18	0.79	0.93	0.41
MgO	4.67	5.18	10.87	6.93	7.73	12.00
CaO	26.44	27.40	25.94	26.16	28.98	26.68
Fe ₂ O ₃	2.40	2.27	1.92	2.86	3.16	2.09
CO ₂	37.70	38.30	36.17	34.28	38.14	38.18
H ₂ O	1.64	0.99	1.76	1.30	1.50	2.10
res.	1.30	2.40	10.30	11.12	2.72	6.48
	99.74	99.68	100.34	99.80	99.55	99.70



Fig. 42. Arsenopyrite (white) mainly located at the outside of the vein and around an ankerite fragment (dark gray) embedded in calcite I (light gray). Chalanches, 1 x.

The ankerites of this group constitute one of the younger mineralization phases, presumably of Alpine age, since some (Peyerère, Longerolle, 20) occur in folded Triassic sediments and none has been disturbed by tectonic movements.

They often form large euhedral crystals, featuring the characteristic curvature of the rhombohedral faces, fig. 41.

Other conclusions that can be drawn for the chemical behaviour of ankerite comprise the tendency of ankerite to lose iron and manganese upon recrystallization (Les Ruines, I and II) and to approach the ideal Ca : (Fe + Mg) ratio. This tendency for ideal cationic ratio is also met with ankerite that has not originated from replacement in situ, but has been deposited from a hydrothermal solution, such as met with the Grande Bois (29), Malrocher (96) and Molliet (88) deposits.

Ankerites thus help to establish the paragenesis and vein type, and yield information about temperature of deposition and recrystallization phenomena.

The complete results of the chemical analyses are tabled.

7 Annabergite and erythrite

Annabergite is a common alteration product of nickel-arsenides and has been recorded in the Belledonne from two localities: Chalanches (analyzed by Berhier, 1819) and La Motte-les-Bains (analyzed by Gueymard, 1854). Apparently only the larger Ni-deposits have led to the formation of secondary minerals. The other deposits containing nickel solely as an accessory element are not mentioned for annabergite in older reports.

An analysis of an alteration zone occurring at Chalanches as a fissure filled by descending solutions reveals 8.8% erythrite and 22.6% annabergite, which is remarkable high, since the substance worked on does not contain any observable green matter. Specimen from Chalanches kept in the Teyler's Museum in Haarlem present macroscopically recognizable annabergite.

8 Antimony

Native antimony has been mentioned together with allemontite. Contrary to arsenic it does not display black etching on exposure to humid air. Intergrowths of allemontite and antimony can be recognized by the differential polishing hardness (antimony is softer than allemontite).

9 Aragonite

Mine waters, or other subterranean streams passing through the Triassic formations on the western flank of the Belledonne (Henrie-adit of Taillat (72) yield on outcrop beautiful incrustations of aragonite.

10 Argentite

though intensively searched for, none of the silver-bearing

inclusions of galena could be identified as argentite. Argentite is only known from the Chalanches deposit, where it is formed both by ascendant and descendant solutions.

As a hypogene product it occurs in veinlets or irregular spots in polybasite and pyrargyrite or as fringes between polybasite and native silver. It also occurs in larger masses replacing pyrargyrite, and then it displays cuneiform twin lamellae (crystallization temperature above 179°). Rapid observation of freshly polished samples of polybasite in tempered light at high magnifications allows the observation of light etching starting in argentite spots.

Argentite of descendant origin is common as small irregular specks in fissures filled with alteration products. The specks are observable only at high magnification. They do not display light etching, a phenomenon so characteristic of argentite, which may be due to a coating produced by the polishing process of the resin-impregnated specimen.

The analysis in par. 30 shows that argentite may be a major constituent of descendant fissure fillings of Chalanches.

11 Argentopyrite-group

One of these rare minerals could be identified among the silver-bearing vein minerals of Chalanches, in a sample provided by Teyler's Museum in Haarlem. Because of its polishing hardness (slightly higher than pyrargyrite), very strong bireflectance (of a pyrrhotite-like colour-scheme, and cyclic twinning (aragonite-type) one is presumably dealing with an argyropyrite-frieseite member of the series.

It occurs as young veinlets in a pyrargyrite-proustite mineral, which in turn replaces native arsenic. Like pyrrhotite, argyropyrite alters in an oriented mass of marcasite and pyrite.

Other occurrences from which argyropyrite has been described, are all typical Co-Ni-Ag-Bi-parageneses (Ramdohr, 1960). Possibly argyropyrite is not so rare at all and may have been taken for pyrrhotite because of equal colour and mode of alteration.

12 Arsenic

Native arsenic is known from Chalanches where it occurs intricately intergrown with allemontite or as individual masses replacing native silver I.

13 Arsenopyrite

Arsenopyrite is limited to the Chalanches, Bonvillard (108) and St. Paul deposits. It seems to belong to one of the younger mineralization phases. The proper setting in the paragenesis, however, of minerals like arsenopyrite, pyrite and magnetite, is difficult to establish, because of the strong tendency of these minerals to form euhedral crystals (even hollow crystals of euhedral outlines may be formed) and their ready recrystallization ability. The latter feature may explain why arsenopyrite in the Belledonne belongs to the younger suite contrary to its position

in other Bi-Ni-Co-Ag-deposits.

In Chalanches, for instance, the detailed mutual age-relations are such as to argue for a younger age than calcite I, although it forms the linings of the calcite-ankerite veins (fig. 42).

In reflected light arsenopyrite is distinguishable by its rhombic sections from löllingite, that, according to a (doubtful, Groth, 1885) description of Frenzel (1875) also should occur at Chalanches.

14 Asbestos

Asbestos with calcite and epidote are commonly associated in veins in the amphibolitic rocks of the central part of the Belledonne Range. Occasionally these minerals are accompanied by ankerite, dolomite or pyrite. Such ankerites, however, are distinct from their ore-bearing equivalents by their low iron content (see Par. 28, dolomite). The asbestos-calcite veins are products of retrograde metamorphism of basic and ultra-basic rocks, and as such may be of Hercynian age (Kalsbeek, 1962).

15 Azurite

It is remarkable, that although both azurite and malachite are common alteration products of copper-bearing minerals, azurite is strictly confined to tetrahedrite-bearing veins and, as such, is common in the Aiguebelle region.

16 Barite

Barite belongs to the old mineralization suite where it constitutes one of the youngest formations. In the Belledonne it is confined to the Allemont and Aiguebelle ore districts (Chalanches, Roche Moutas, Lac Crop, Les Fruithiers, St. Georges, Montgilbert and Bonvillard). However, Haudour (1956) also noticed barite of a peculiar acicular habit in the Carboniferous of La Mure, apparently belonging to an Alpine mineralization. With the exception of the Montgilbert deposit, barite only occurs as a minor constituent of the vein. It commonly is associated with hematite.

In contrast to the carbonates it displays very little tendency to become recrystallized. Where the effects of disruption of sulphides embedded in siderite or ankerite have almost completely been obliterated by recrystallization, sulphides embedded in barite yield clear examples of the stress to which the ores in certain districts of the Belledonne have been subjected (fig. 91 and 93). This feature accounts for the rare occurrence of barite in the younger paragenesis.

17 Bismuth

The identification of bismuth (not previously recorded) among

the Co-Ni ores of Chalanches completes the picture of this deposit as a typical representative of the Co-Ni-Bi-Ag-suite. Bismuth occurs as arbitrarily shaped crystals in a compact or arborescent mass of safflorite. Shape and position of the (small) bismuth crystals with respect to safflorite resemble those of replacement relics. Their occurrence as innermost part of arborescent textures is very typical for this type of ore deposits and has been described many times before.

18 Bornite

Bornite is commonly associated with chalcopyrite in a non-recrystallized vein type, and thus prevails in the Allemont and Aiguebelle ore districts. There are two modes of occurrence:

- as small irregular patches equally distributed over the host (chalcopyrite), probably resulting from concentration of exsolution drops. Sphalerite occurs in a similar way with this chalcopyrite (Sapey).
- or as larger blebs associated with chalcopyrite, but forming individual aggregates.

In the latter type of bornite (occurring at Chalanches and the Col de Sifflet) exsolution lamellae of chalcopyrite are not uncommon. This exsolution should point to high crystallization temperatures (475° respectively 300° according to Schwartz (1931) and Sugahi (1950). Natural conditions, however, are not always matched in the laboratory, and the actual crystallization temperatures may depart essentially from the values mentioned. Anyhow they point to meso-thermal crystallization conditions, since chalcopyrite (re)-crystallized under epithermal conditions is never accompanied by bornite in a disseminated texture. Bornite has also been described by Lacroix (1910) from the Prunières deposit in the La Mure district.

Occasionally bornite has been altered to, or is associated with covellite.

19 Bournonite

Bournonite, noticed by Termier (1897) from Peychagnard (La Mure) and Hintze (1904) from Allevard, is very common in the Belledonne and La Mure ore districts. It occurs in close relation to the old mineralization suite. In all instances it is accompanied by tetrahedrite, galena and often also by boulangerite. The relation among these four minerals is such as to suggest a reaction series of increasing lead-content (fig. 43, 44 and 46). This sequence has also been described by Friedrich (1933) from the Steiermark ore district in the Eastern Alps.

This paragenesis is of remarkable uniformity among the Belledonne ores and occur with all tetrahedrite and galena-bearing veins, either young ones or veins of the old mineralization suite that have undergone (complete or partial) recrystallization. This relation to recrystallization phenomena is so persistent that bournonite and boulangerite are absent in the older non-recrystallized parts of a vein, in the recrystallized parts of which they do occur. The Chalanches and

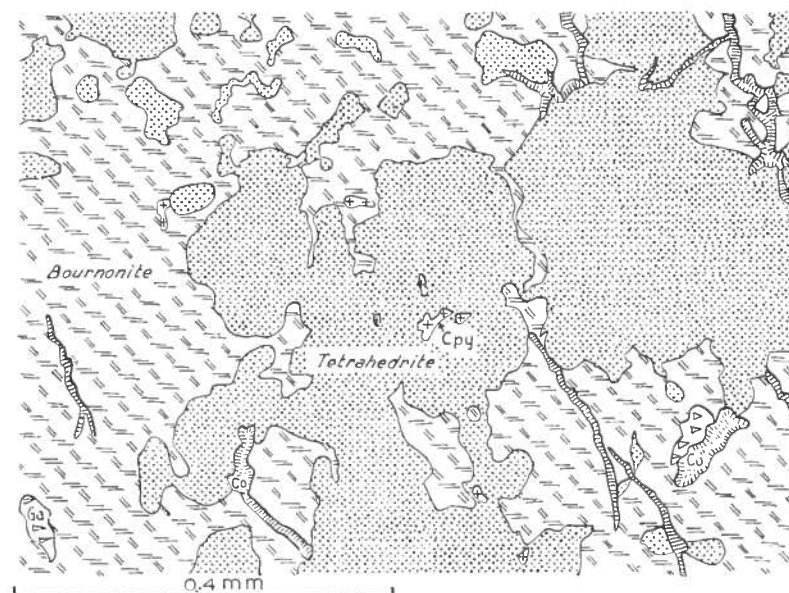


Fig. 43. Chalcopyrite (Cpy) and tetrahedrite replaced by bournonite and galena (Ga); veinlets of secondary covellite (Co). Galena is confined to bournonite, chalcopyrite or tetrahedrite. Les Ruines.

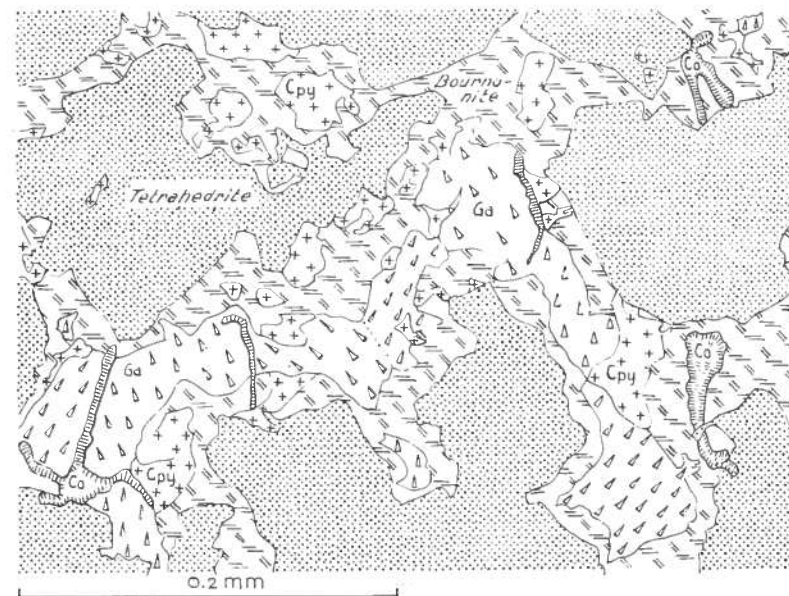


Fig. 44. Bournonite as reaction product between galena and tetrahedrite. Clusters of small chalcopyrite crystals at the borders of tetrahedrite. Remoud.

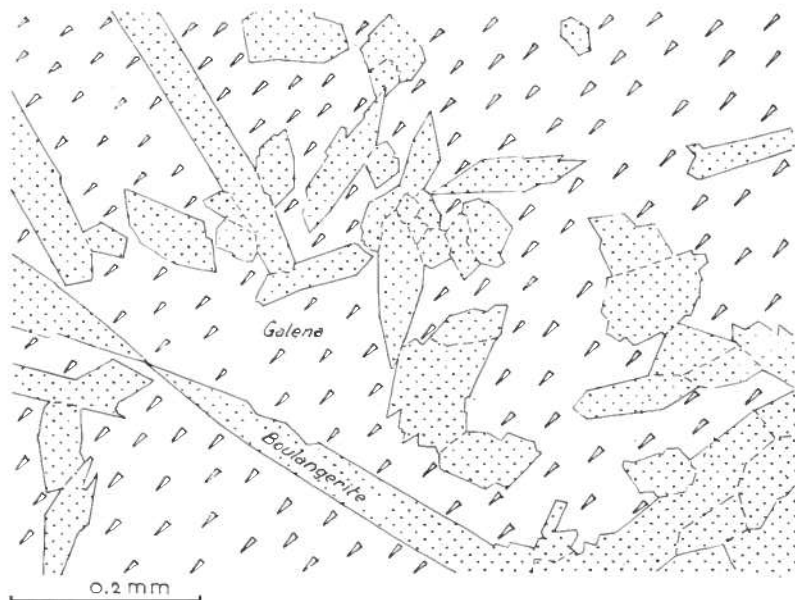


Fig. 45. Needles of boulangerite in galena. Peyrère-Longerolle.

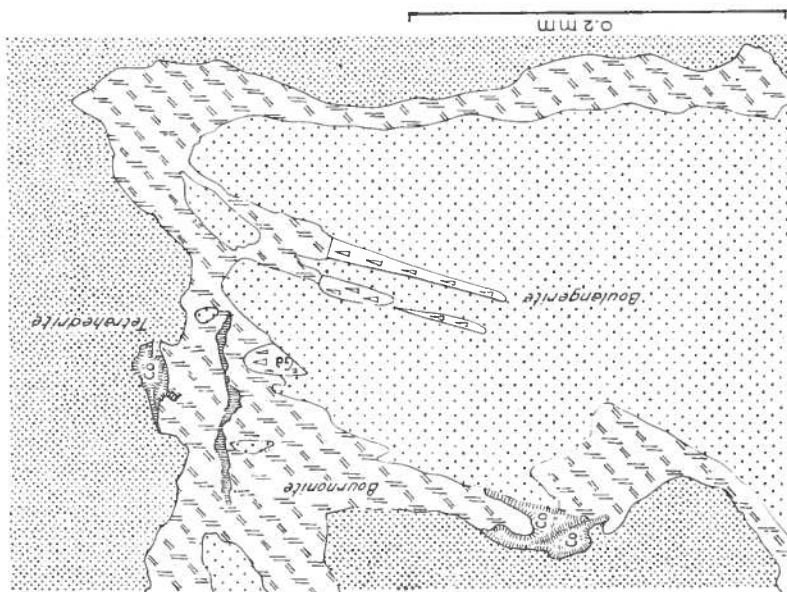


Fig. 46. Boulangerite and bournonite as reaction products of tetrahedrite and younger galena (Ga). Chalanches.

Bonvillard deposits provide good examples of this phenomenon.

The bournonite occurrences of the La Mure district described by Sarrot-Reynauld (1957) are concurrent to this rule. There, too, bournonite is met in veins of Alpine age being related in space with the meso-thermal veins of the crystalline basement.

In those parts of the Belledonne's External Zone, where veins of the older type are absent and only young veins (of presumably Alpine age) occur bournonite is also lacking. This is a consequence of the impoverished mineralogy of such epithermal deposits.

Bournonite has not been chemically investigated. It has been identified with the ore microscope. Age relations are readily established since bournonite is anisotropic and generally furnished with a complex set of twin-lamellae.

20 Boulangerite

Boulangerite is a relatively rare mineral. Its identification among tetrahedrite and galena-bearing veins intersecting Carboniferous coal beds of the La Mure district has been subject of a publication by Haudour (1956). In these veins it occurs as megascopically recognizable fine fibrous crystals yielding the boulangerite X-ray diagram. The author's ore-microscopical investigations, however, have revealed boulangerite not to be so rare at all.

Boulangerite is not easy to recognize and may be held for jamesonite, which is also very similar in chemical composition. The marks of distinction listed by Ramdohr (1960) may be of much help for the definite identification, but are necessarily somewhat generalized, since the chemical composition of boulangerite is not a constant one. Solid solutions with falkmanite are possible (Ramdohr, 1939). The authors final determination was made with the aid of X-ray powder diagrams for those deposits, where boulangerite is relatively abundant (Peyrère-Longerolle and Chalanches). The roentgenographic identification, however, no more is simple with these lead-sulphosalts, since their reflections are faint and may vary considerably in intensity as a result of preferred orientation of the powdered mineral, which has as distinctly fibrous habit.

In addition to Ramdohr's data (1960) on the ore-microscopical characteristics of boulangerite, the following should be mentioned: the dark-blue and brown colours as effects of anisotropism. These are very striking, even with oil-immersion objectives, and are lacking with jamesonite. The reflectivity is less than that of galena, but contrary to Ramdohr's opinion the author regards the olive- to blue-greenish colours as distinct. They make galena appear to be of a reddish tinge. The bireflectance scheme of pale bluish-green to olive green displayed by the Belledonne's boulangerite has been attributed by Ramdohr (1960) to falkmanite. The possibility that we are dealing here with a member of the solid solution series: boulangerite-falkmanite, may be doubted since the values for the lattice spacings come close to those of true boulangerites, and the lattice spacings 3.10 and 3.31 of falkmanite are absent.

{hkl}	Boulangerite of Longerolle	Boulangerite of Pribram (Czech)	Boulangerite of Wolfsberg (Germ.) according to Hiller, (1938)
{004}	3.71	3.70 st. 3.21	3.70 st. 3.21
{600}	3.00	3.00	3.00
{305} {205}	2.80 st.	2.80 v.st.	2.80 v.st.
{305} {114}	2.69	2.69	2.69
	2.59		2.59
{414} {604}	2.31	2.33	2.34
		2.23	2.23
		2.14	2.14
		2.01	2.02
{804} {407}	2.00	1.92	1.92
{804} {008}	1.86	1.86 st.	1.86 st.
{804} {904}		1.76 broadened	1.76
	1.47	1.47	1.47

Because of the absence of the 3.21, 2.23 and 2.14 d-values the presence of falkmanite in the Longerolle deposit cannot be excluded, although it is very unlikely, since Haudour's X-ray powder diagram from a lead-sulpho-salt of Psychagnard undoubtedly points to boulangerite.

Boulangerite has been taken for antimonite in the occurrences of Laffrey (Lacroix, 1893), and probably also in Chalanches (Hericart de Thury, 1806) and Esserts-Blay (Hollande, 1911), since in the latter deposits the author only boulangerite has met.

As was mentioned for bournonite, boulangerite occurs in a typical paragenetical position being a reaction product of tetrahedrite-bournonite with galena. The figure (46) gives the mutual relations.

Boulangerite of the Longerolle deposit has been replaced selectively by cerussite, whereas its host (galena) has hardly been attacked (fig. 45, of an unaltered specimen).

21 Calcite

According to their mode of occurrence three types of calcite can be discerned:

a Calcite in barren veins from the basic rocks of the Inner Zone.

In this vein type calcite is accompanied by asbestos epidote, chlorite and other minerals that have been produced by the retrograde metamorphism of ultrabasic or amphibolitic rocks. Alteration of plagioclase yielded calcite, alteration of hornblendes or pyroxenes yielded epidote and chlorite. This vein type is mainly located on faults in the Inner Zone, the same ones on which the ore veins are situated and therefore it may have been intermingled with type b 1, from which it can be distinguished by its substantially higher Fe/Mn ratio (analyses are tabled).

	23 CHALANCHES calcite CO ₂ calculated	23 CHALANCHES calcite CO ₂ calculated	27 CHAMROUSSE 60% calcite s% Fe-hydroxides	29 GRANDE BOIS calcite	29 GRANDE BOIS 80% calcite 7% dolomite	30 ROCHE NOIR 90% calcite s% ankerite	32 MALPOURCHÉ 80% calcite s% sid., s% ank.
FeO	4.75	trace	--	--	--	2.59	6.35
MnO	2.06	0.32	1.15	1.81	2.63	5.40	3.96
MgO	0.25	trace	1.46	2.04	2.40	1.74	1.31
CaO	49.58	55.72	26.96	52.60	34.50	47.74	34.40
Fe ₂ O ₃	--	--	12.20	1.43	10.50	7.38	5.64
CO ₂	42.36	43.96	21.37	41.34	28.00	36.12	34.76
H ₂ O	--	--	3.10	7.54	2.50	0.98	2.56
res.	--	--	33.84	0.64	19.14	4.94	9.64
	100.00	100.00	100.01	100.40	99.67	99.19	98.62

	33 TROIS LAUX 90% calcite 2% siderite	EPIDOTE- CALCITE VEIN NEAR P.D.L. COCHE 30% calc., s% dolom. s% Fe-hydroxides	20 PEYERERE 25% calcite 25% dolomite	BOUT DU MONDE 85% calcite 10% Fe-hydroxides	CHAPELLE DU B calcite	24 PONT ROUGE 85% dolomite 10% calcite	29 GRANDE BOIS 50% dolomite 25% calcite
FeO	1.64	--	0.67	1.09	--	0.72	1.47
MnO	1.34	1.02	0.17	0.14	0.12	1.32	1.63
MgO	0.34	0.88	0.53	--	0.83	16.66	8.41
CaO	53.62	25.70	33.20	43.60	52.28	31.02	27.06
Fe ₂ O ₃	1.18	12.29	12.60	9.98	4.71	1.84	5.82
CO ₂	40.80	19.20	30.74	35.24	39.80	42.34	30.08
H ₂ O	0.73	3.32	4.70	3.38	0.62	1.30	1.57
res.	0.10	36.70	12.68	5.62	1.70	5.02	23.32
	99.83	99.11	99.29	99.05	100.06	100.22	99.36

b Calcite from siderite-veins

1. Manganiferous calcite

Calcite of the previously mentioned genesis has probably been incorporated into some of the ore-bearing solutions since in both instances they are situated on the same faults (in particular the faults bordering the amphibolites). In the case of a hybrid genesis, however, the share of ore-bearing solutions in the formation of calcite, remains quite large. All calcites of the Allemont region have high manganese contents. In this aspect they depart from the calcite of retrograde metamorphic genesis.

This type of calcite only occurs in the Allemont region, and is absent from other areas even those that contain ores of the same paragenesis. The deformation to which these calcites have been subjected was so strong that fine-grained, highly distorted crystals were the result (Chalanches, Roche Noir, Malpourchié and Trois Laux).

2. Unstrained, chemically pure calcite

This calcite incidentally occurs in all kinds of paragenesis as one of the younger mineralization phases (Grande Combe, Les Ruines, Chalanches II and many others). Strong deformation did not occur in this calcite, some straight twin-lamellae being the only possible stress-effects. At Chalanches it makes up the main gangue of the Ag (possibly also the As-Sb-Co-Ni) suite. The paragenetical situation of deposits bearing this hypogene strain-free calcite is too different, to be attributed to a definite mineralization phase.

c Calcite segregated from Mesozoic country rock

Although of a genesis different from that of the ore bearing solutions this calcite, too, takes part in the formation of the ore deposits. It only occurs in ore deposits that have been emplaced by Alpine orogeny (Longerolle-Peyerère, Bout du Monde). In consequence of their genesis their Mn-content is very low.

22 Cerussite

Cerussite is a common alteration product of galena. Supergene alteration starts with the scattered growth of small cerussite nuclei in galena, gradually spreading out over the whole crystal. In this stage covellite is also formed. There are only few galena deposits that have not been attacked by alteration.

23 Chalcopyrite

Although chalcopyrite in only a few veins (Col de Sifflet,

St. Georges, Remoud, Prodin) belongs to the main constituents, yet it is the constant companion of sulphide-bearing ore veins. The typical environment of chalcopyrite is a deposit of the older paragenesis, in the younger one it is absent or comprises only insignificant quantities.

Chalcopyrite generally occurs in association with sphalerite, tetrahedrite and galena. The relation with sphalerite is such that only exsolution drops of chalcopyrite in sphalerite occur, but not the reverse situation of star-shaped sphalerite specks in chalcopyrite. Apparently, the crystallization temperatures have not been in the catathermal range. The stages of the process of exsolution of chalcopyrite from sphalerite will be described in the section on sphalerite.

The intergrowths with tetrahedrite are of metamorphic origin. A simultaneous process of recrystallization and blastesis has brought about the typical Rammelsberg intergrowths (fig. 90) described by Ramdohr (1953). Chalcopyrite forming part of these structures (Remoud, Prodin, Malrocher) has been strongly deformed, as is shown by its distorted twin-lamellae and small grain size. The ability to a complete restoration of strained crystals apparently is not as great as with galena, which occurs in the same deposits, but has a coarse granoblastic fabric.

In instances chalcopyrite has been exploited for its gold content (Chalanches, La Cochette, Le Merle de Theys and Allevard) ranging from 12 to 50 ppm Au (Gueymard, 1844, and Nicolet, 1931).

A chemical study of chalcopyrite has not been made. Microscopical investigations seem to point to a relation between the degree of anisotropism of chalcopyrite and its environment. Some metamorphosed chalcopyrites occurring in assemblages of supposed mesothermal genesis have a more clearly marked anisotropism (in some instances even a recognizable birefractance, Chevrette) than chalcopyrite of the younger paragenesis.

24 Chlorite

In order to test the possible application of Angel's (1939) theory on the origin of siderite and ankerite to the genesis of the Inner Zone's ore deposits, analyses have been made of the chlorite that has been formed as result of retrograde metamorphism of amphibolites. If these show low iron contents as compared with the amphibolites, pyroxenes or biotites, this would mean that the retromorphism has yielded an iron excess, that could possibly be fixed by siderite or ankerite. Two samples have been analyzed, one pertaining to the ore body (Roche Noire), in which chlorite is contemporaneous with stilpnomelane and magnetite and another from the wall-rock of the Malpourchié vein (fig. 63).

A calculation of the results on the basis of the standard composition of chlorite: 16 OH to 12 (Fe^{2+} , Fe^{3+} , Al, Mg, Mn, Ca) to 8 (Si, Al) appeared to be difficult to realize, because of uncertainty regarding the purity of the wall rock sample. The sample is probably contaminated with quartz, feldspar and rutile.

	Wall rock chlorite Malpourchié	Vein-chlorite Roche Noire
SiO ₂	31.72 quartz 8%	23.30
Al ₂ O ₃	16.26	19.02
Fe ₂ O ₃	12.05	10.75
FeO	23.32	27.80
TiO ₂	0.59	0.03
MnO	0.63	0.61
MgO	4.89	7.98
CaO	0.19	0.15
Na ₂ O	0.20	0.20
K ₂ O	0.20	trace
P ₂ O ₅	0.26	0.23
H ₂ O	9.13	10.57
	<hr/> 99.44	<hr/> 100.64

The vein chlorite has been calculated as ripidolite with a Fe (total) / Fe (total) + Mg ratio of 0.85 and a Si/Al(tetrahedral) ratio of 5.5 : 2.5. Ripidolites of similar composition have been described by Hallimond (1939) and Tschermak (1891) from the ore deposits of Cornwall. (the nomenclature is from Deer et al. 1962).

The optical data are also concurrent to those of ripidolite: N_{α} (yellow) : 1.646; N_{γ} (dark green) : 1.651; $N_{\gamma} - N_{\alpha}$: 0.005; - $2V_x$: 10^0 ; anomalous interference colours are lacking.

Chlorite from the wall rock of the Malpourchié deposit has almost the same optical properties:

N_{α} (yellow) : 1.649; N_{γ} (dark green) : 1.654; $N_{\gamma} - N_{\alpha}$: 0.005; - $2V_x$: small (5^0); anomalous interference colours are lacking.

The chemical analyses, however, seem to be different because of contamination, but after subtracting quartz, the chemical composition also comes very close to the chlorite of Roche Noire.

These highly ferroan chlorites are not incidental cases, but have been identified in many instances where the grain size of chlorite has permitted an accurate determination of optical properties (v.d. Wart, 1959). They even have been noticed from calcite-epidote veins that result from retrograde metamorphism of the amphibolites.

Hence, the idea of Angel about the genesis of siderite and ankerite does not apply to the origin of the siderite of the Belledonne's Inner Zone, since the alteration products still possess remarkably high iron-contents. Moreover, the common presence of siderite in the Belledonne's Outer Zone, where iron-bearing silicate minerals do not occur in any significant quantity, is no more compatible with Angel's hypothesis.

25 Cinnabar

The occurrences of cinnabar in the Belledonne are interesting, since they reveal a certain relation between the ore deposits of Chalanches and the Alpine ores of the La Mure district. In the La Mure district cinnabar has been met in metalliferous veins in

Liassic limestones (St. Arey, described by Schreiber, 1798) and in cavernous limestones of Triassic age (Prunières, described by Gras, 1851).

The notification of cinnabar by Schreiber (1784) and Héricart de Thury (1806) from the Ag-suite of Chalanches is anomalous for this kind of paragenesis and possibly bears relation to other inconsistencies of this Ag-suite, such as its post-tectonic emplacement, which contrasts to the metamorphic fabric of the preceding carbonate suite, and its frequent recrystallization phenoma (yellow sphalerite).

26 Covellite

About the mode of occurrence of covellite it is remarkable to note that it is relatively rare as an alteration product of chalcopyrite or tetrahedrite, but very common with altering galena (Argentine, Chalanches). Replacement of galena by covellite occurs in irregular spots or veinlets following the cleavages. It is not known whether the copper-content of covellite should be attributed to bournonite inclusions in galena or whether it has been introduced secondarily.

27 Coronadite

Coronadite, or Pb-hollandite, is a very rare mineral, and although occurring in only one deposit (Richesse) in very small quantities, it is described in detail here since its presence in the Belledonne constitutes the fifth occurrence in the world.

The other occurrences are:

Coronado vein, Arizona (Lindgren, 1933), Bou Tazoult, Marocco (Orcel, 1932), Broken Hill, N.S. Wales (Ramdohr, 1960), Kurgashinkan, Uzbekistan (Golovanov, 1960). In the deposits mentioned above it occurs either as interaction products of altering galena in a pre-existing manganese deposits (Bou Tazoult and Kurgashinkan), or it is formed by a simultaneous alteration of galena and manganiferous minerals in a vein (Broken Hill). The newly found occurrence of Richesse, near Bourget-en-Huille, Savoy, is of the latter type.

Supergene altering siderite forms an indigenous box-work of goethite (altering to hematite) and manganese-oxides, the latter constituting the linings of the box-work. The first manganese-oxide to form is a soft, crypto-crystalline psilomelane-like mass that grows in botryoidal structures. In these irregular cavernous masses a hard, yellowish mineral (pyrolysite) develops along with a white, clearly anisotropic, microcrystalline manganese-oxide that takes an excellent polish, if not too porous. This mineral displays a distinct birefractance, however, without colour effects. According to data of Ramdohr (1960) it may be taken for cryptomelane, hollandite or coronadite. An X-ray sample has been prepared by removing the questioned mineral from the polished specimen with a micro-drill. The X-ray powder diagram gave only faint reflections due to lack of material, the overwhelming masses of impurities and possibly the poorly crystalline nature of the sample. A reference diagram of coronadite from Bou Tazoult yielded clear reflections.

Subtracted for those of goethite the reflections of the cryptomelane-like mineral are:

{hkl}	Hollandite II of India Byström, 1950	Coronadite of Bou Tazoult Frondel, 1942	Richesse, Savoy
{202}	3.463 st.	3.466 st.	3.45 st.
{103}	3.105 v. st.	3.104 v. st.	3.11 v. st.
{211}	2.406 st.	2.400 st.	2.39 st.
{204}{402}	2.198 st.	2.205 st.	2.21 st. (broad)
{204}{310}	2.172 st.		2.17 st.
{013}	2.146 st.	2.155 st.	2.14 st.

The diagram confirms the idea that we are dealing with one of the members of the cryptomelane-coronadite group. A definite identification only appeared to be possible by a chemical analyses. A sample has been prepared in the same way as happened for the X-ray analyses: 97 milligram was all the material that could be made available.

Fe ₂ O ₃	28.0	} goethite
H ₂ O + O	13.5	
K ₂ O	1.3	} cryptomelane
MnO	3.5	
MnO ₂	34.5	} coronadite
PbO	12.9	
res.	3.5	} quartz
	<hr/> 97.2	

H₂O + O have been determined as loss on ignition. Fe₂O₃ has been precipitated by the acetate method. The combined manganese oxides were determined by precipitation of MnO₂ from a neutral solution by bromine water. The MnO : MnO₂ ratio has been calculated according to the coronadite (Pb) and the cryptomelane (K) composition. Pb has been determined as PbSO₄, the precipitate being identified by microchemical reactions (KI; CsCl: KI + CsCl) and sodium rhodizonate (for excluding Ba). Potassium has been separated by the sodium-cobalt-trinitrite method.

Thus, notwithstanding contamination, coronadite (ideal composition: Pb Mn^{II} Mn^{IV} O₁₆) forms the bulk of the sample. Cryptomelane, apparently, also occurs. The ore-microscopical properties noticed by the author will not be mentioned here, because of the poor development of coronadite crystals in the investigated samples, and their identity with those from Bou Tazoult, where far more representative specimens occur (Orcel, 1932).

28 Dolomite

Dolomite, as a vein constituent, is known from the Grande Bois and Pont Rouge deposits. Its paragenetical relations are similar to those of ankerite from other veins in the Allemont ore

district. This constitutes the reason why many ankerites are regarded as reaction products of a siderite-bearing solution and previously existing or simultaneously formed products of retrograde metamorphism. This hypothesis explains the broad variation in composition (see ankerite) noticed for these ankerites, since the composition depends on the relative amounts of siderite and dolomite that have been involved in the reaction. The feature, that siderite is rare or insignificant in veins, where ankerite of low iron-content or dolomite occurs is concurrent to the idea of a hybrid origin. Moreover, highly ferroan ankerite has only been met in veins where siderite prevails (Malpourchié, Trois Laux). The composition of two dolomites is mentioned in the calcite table. The Grande Bois dolomite is diagrammatically represented in fig. 36 with ankerite.

29 Galena

Galena is one of the main minerals of the Belledonne metalliferous province. In some cases it is even the main ore (Mont Jean, Chalanches, Tilleray, Richesse, Fosse Guerre, Perrelle, Les Mouches, Argentine and Bonvillard). The distribution of galena over both types of ore deposits is such that it occurs in the older paragenesis in workable quantities, whereas the quantities of galena in the younger veins are only of mineralogical interest. The latter fact is remarkable, since of all sulphides galena shows the greatest ability to recrystallize. The strongly deformed fabrics so common with chalcopyrite and tetrahedrite, never has been observed in galena (fig. 47 and 89). Even the Argentine deposits, where galena still is present in its original assemblage (high Bi-content, and associated with pyrrhotite) shows a granoblastic fabric (fig. 48). Structure-etching has been performed with Fackert's solution (85% HNO₃ of S.G. : 1.2, and 15% alcohol) or 1 : 1 diluted HCl. The results for both etching methods are rather poor as compared to those of sphalerite. They are, however, sufficient to recognize the textures.

Galena has been analyzed for Bi, Ag, and Cu; Bi by a spectrophotographical method, relative error: 5%; Ag by roasting off the lead, and Cu with the aid of paper-chromatography.

The results of the analyses are listed below:

	%- Ag	%- Bi
Mont Jean	0.13	0.13
Longerolle
Sapey	not.det.	0.02
La Fare	0.09	0.02
Tilleray	0.09	0.02
Pierre Herse	0.04	0.03
Fond de France	not.det.	0.03
St. Hugon	not.det.	0.07
Previoux	0.10	0.02
Perrelle	0.09	0.03
Richesse	0.08	0.08



Fig. 47. Granoblastic recrystallization fabric of galena and sphalerite. Galena recrystallized to a coarser grain size than sphalerite. St. Hugon.

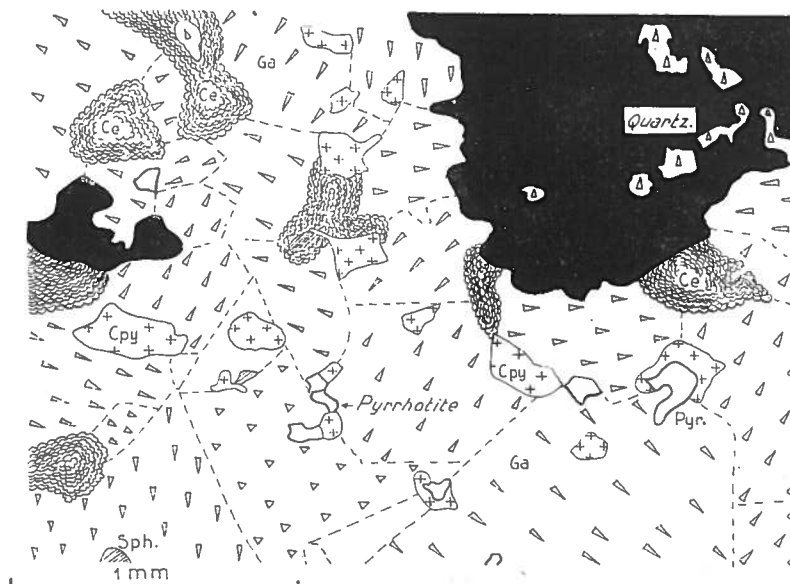


Fig. 48. Coarse recrystallization fabric of galena. Recrystallization occurred without major changes of chemistry, such as indicated by high Bi-content and the scattered presence of pyrrhotite (Pyr.) and chalcopyrite (Cpy). Supergene replacement by cerussite (Ce). Argentine.

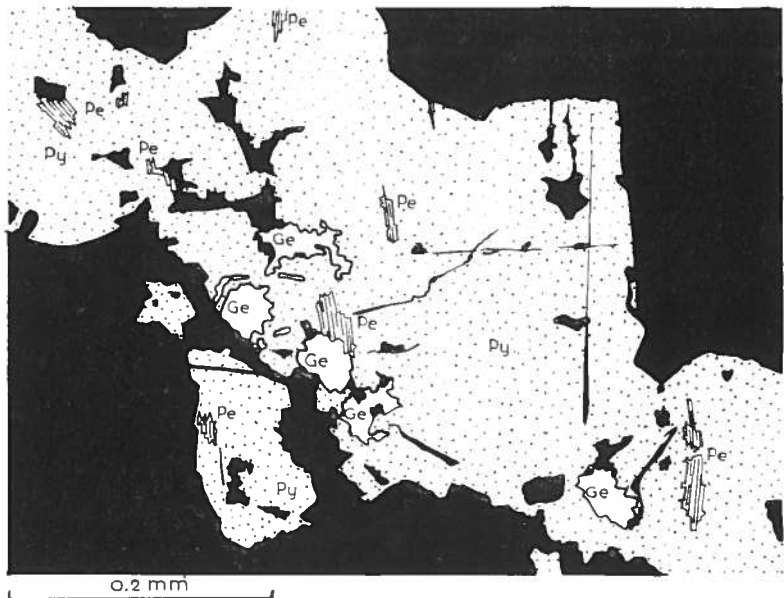


Fig. 49. Exsolution lamellae of spindle-shaped pentlandite (Pe) in pyrrhotite (Py). Gersdorffite (Ge) with "corroded" outlines. Replacement relics, or porphyroblastic growth? Argentine.

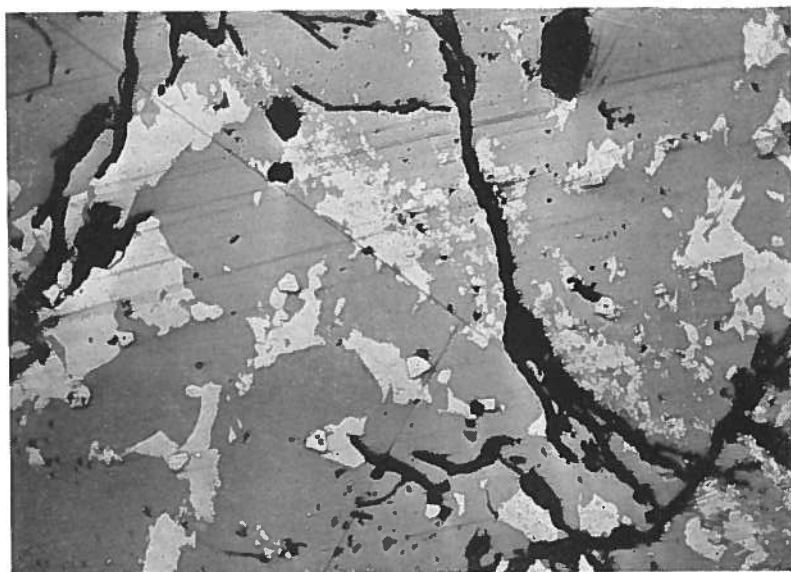


Fig. 50. Trains of small gersdorffite crystals (high relief) of euhedral outlines (cubo-octahedron-sections). Some gersdorffite crystals show cavities at their centres. Intricate intergrowths of tetrahedrite (dark gray) and chalcopyrite (light gray). Remoud, 100 x.

	%- Ag.	%- Bi
Montgilbert	not.det.	0.11
Les Mouches	0.14	0.03
Bonvillard	0.10	0.03
Argentine	0.08	0.19

The copper-contents are not recorded, since they vary widely and are due to chalcopyrite inclusions.

Some galena's have remarkably high Bi-contents, so high that they should be attributed to catathermal genesis, according to Schroll (1955) and Baumann (1958). Other Bi-contents, however, occurring in the same paragenesis are substantially lower. These differences cannot be attributed to recrystallization alone, since recrystallization occurred in all deposits. Apparently the disruption and subsequent entrapment by quartz has caused the galena to lose its bismuth-content, whereas the silver-content has hardly been affected by this process. Only galena from the younger vein type has also lost part of its silver (Longerolle, Pierre Herse).

A Pb-isotope determination has been performed by the F.O.M. laboratory for mass-separation. The results are listed below:

	Pb ²⁰⁸	Pb ²⁰⁷	Pb ²⁰⁶	Pb ²⁰⁴
50 Tilleray	52.50 ± 0.06%	21.23 ± 0.12%	24.96 ± 0.11%	1.313 ± 0.16%
85 Pierre Herse	52.71 ± 0.04%	21.16 ± 0.16%	24.84 ± 0.19%	1.294 ± 0.43%
20 Longerolle	52.43 ± 0.14%	21.25 ± 0.16%	25.01 ± 0.16%	1.318 ± 0.16%
7 Mont Jean	52.44 ± 0.12%	21.25 ± 0.19%	25.00 ± 0.16%	1.309 ± 0.36%
17 Le Sapey	52.38 ± 0.09%	21.21 ± 0.23%	25.10 ± 0.16%	1.309 ± 0.19%
102 Perrelle	52.49 ± 0.09%	21.22 ± 0.17%	24.98 ± 0.10%	1.311 ± 0.35%
103 Richesse	52.55 ± 0.08%	21.22 ± 0.11%	24.92 ± 0.12%	1.313 ± 0.43%
106 Montgilbert	52.45 ± 0.13%	21.23 ± 0.16%	25.04 ± 0.21%	1.289 ± 0.67%
108 Bonvillard	52.51 ± 0.11%	21.20 ± 0.28%	24.99 ± 0.12%	1.304 ± 0.62%
112 Argentine	52.38 ± 0.06%	21.32 ± 0.39%	24.97 ± 0.39%	1.329 ± 0.17%
104 Les Mouches	52.55 ± 0.21%	21.21 ± 0.31%	24.91 ± 0.25%	1.330 ± 0.40%
90 Fond de France	52.22 ± 0.09%	21.45 ± 0.18%	25.01 ± 0.10%	1.327 ± 0.47%
92 St. Hugon	52.49 ± 0.15%	21.21 ± 0.25%	24.98 ± 0.19%	1.325 ± 0.45%

	$\frac{Pb^{206}}{Pb^{204}}$ $\frac{\beta}{\alpha}$	$\frac{Pb^{207}}{Pb^{204}}$ $\frac{\beta}{\beta}$	$\frac{Pb^{208}}{Pb^{204}}$ $\frac{\beta}{\gamma}$	$\frac{\Delta\beta}{\Delta\alpha}$	Age in Ma ± 75 Ma
Tilleray	19.012	16.170	39.985	0.6083	230
Pierre Herse	19.198	16.359	40.741	0.6162	316
Longerolle	18.974	16.115	39.768	0.6050	193
Mont Jean	19.107	16.238	40.077	0.6094	242
La Sapey	19.177	16.205	40.024	0.6015	153
Perrelle	19.051	16.180	40.022	0.6069	214
Richesse	18.973	16.156	40.011	0.6094	242
Montgilbert	19.424	16.469	40.687	0.6132	284
Bonvillard	19.160	16.254	40.260	0.6077	223
Argentine	18.784	16.037	39.406	0.6090	237
Les Mouches	18.736	15.948	39.521	0.6024	163
Fond de France	18.843	16.164	39.350	0.6188	344
St. Hugon	18.847	16.003	39.606	0.6012	149

For each sample the "model age", P, has been calculated by means of the Holmes - Houtermans (1960) equation:

$$\frac{\beta - \beta_w}{\alpha - \alpha_w} = \frac{1}{137.8} \left(\frac{e^{\lambda_w} - e^{\lambda_p}}{e^{\lambda_w} - e^{\lambda_p}} \right)$$

where

$$\begin{aligned} \lambda &= 1.54 \times 10^{-10} \text{ yr}^{-1} \\ \lambda' &= 9.72 \times 10^{-10} \text{ yr}^{-1} \\ \alpha_w &= 9.56 \quad (\text{representing the mean values of the} \\ &\quad \text{atomic ratios } \alpha \text{ and } \beta \text{ for lead of} \\ \beta_w &= 10.42 \quad (\text{meteoritic origin}) \\ W &= 4.55 \times 10^9 \text{ yr (age of the earth's crust)} \\ 137.8 &= \text{ratio } U^{238}/U^{235} \end{aligned}$$

The differences between the model ages of the individual galena samples are not regarded as being significant, the relative error being rather large with this method of physical age determination. However, apart from a possible error in the absolute values, the model ages point to a Hercynian age, the average value being in the order of 230 ± 50 Ma. This age means that according to geological observations the greater part of the galenas have normal isotopic ratios. With only two galenas (no. 20 and 85) the geological situation is such that the isotope composition must be regarded as anomalous, the geologically inferred age being Miocene-Pliocene (post-to-late-Alpine emplacement). This statement constitutes another confirmation of the hypothesis of Alpine rejuvenation of Hercynian ore deposits.

30 Gersdorffite

Gersdorffite has been identified by X-ray methods from the Argentine and Remoud deposits, where it occurs in very small quantities. The scarcity of material is the reason why a mineralogical or chemical investigation has not been made.

In the Argentine deposit gersdorffite is associated with pyrrhotite and pentlandite. It builds cubic crystals of corroded outlines, and seems to be replaced by pyrrhotite (fig. 49). Special attention, however, should be given to the interpretation of replacement phenomena between minerals such as gersdorffite, pyrite and magnetite and other minerals that have not such a strong tendency to form euhedral crystals. The irregular outlines of these porphyroblasts have often been interpreted as replacement relics, although actually they are of younger age. The assemblage pyrrhotite-pentlandite and gersdorffite has also been described by Koning (1941) from the Sudbury ore district, and should be very rare. It indicates a catathermal genesis of the Argentine deposits, an idea that is also supported by its high Bi-content (Baumann, 1958).

In the other deposits, Remoud, Prodin, and Malrocher, gersdorffite forms perfectly euhedral crystals of cubo-octahedral shape, as shown by the triangular, quadrangular and hexagonal sections in the polished specimen (fig. 5). In some

instances its crystal boundaries also seem to be affected by corrosion, but here strong evidence for a younger age than its host is yielded by the train-like arrangement of crystals, cutting across older structures and minerals (fig. 90).

This gersdorffite displays a clear zonality, the zones possessing two different hardnesses, but the same colour and reflectivity. Probably we are dealing here with the α - and β - gersdorffite of Dunn (1937).

31 Goethite

The name goethite has been used for α - FeO OH such as proposed by Palache et al. (1944), being identical to the German "Nadeleisenerz". Many analyses of siderite actually are analyses of goethite, goethite being its alteration product. The process of alteration of siderite appears from the analyses no. 55 - 69 - 53. There is a gradual loss of magnesium, calcium and CO₃, occurring simultaneously with oxidation of ferrous iron into the trivalent state, and increase of the water content. The analyses of Montchaffrey, Rafour, St. Joseph, Tilleray, Clavette and Maltrait denote a complete transformation of siderite into goethite. Part of manganese may be present as a substitution for iron, another part as manganese-oxides. Goethite, however, does not represent the end stage of the alteration process, it being succeeded by dehydration of goethite to hematite. The formation of hematite microscopically can be followed (fig. 51). The analyses 79 - 31 - 61 and 62 show the dehydration of goethite until hematitization is complete (du Rocher, 62). Manganese cannot substitute for iron in the hematite lattice to the same extent as is possible in siderite. Thus, the Fe/Mn ratio may change during this stage of alteration. Hematitization has only been noticed in the high-level deposits, above ground-water level.

32 Gypsum

Gypsum, has been identified as a vein constituent among the annabergite, erythrite and silver-bearing alteration products of Chalanches. Its descendent genesis is rare and is supposed to result from oxidation of sulphides (Deer et al. 1962). An analysis of a microcrystalline purple coloured fissure filling of Chalanches brought to light that gypsum is the main constituent of the "filons sauvages" of Hericart de Thury (1806). A complete analyses showed the following elements:

Ag	17.8 %	determined as AgCl
Fe ₂ O ₃	4.2 %	weighed precipitate (roasted)
Mn ₃ O ₄	2.5 %	weighed precipitate (roasted)
Ni	7.8 %	as di-methyl-glyoxime-complex
Co	2.9 %	as pyridine - CNS - complex
As	9.2 %	as uranyl complex
S	8.4 %	as BaSO ₄
H ₂ O	13.0 %	by the Penck method
residue	1.1 %	

From the mineralogical composition of the sample the following

mineral content has been calculated:

native silver	9.5 %
argentite	9.4 %
goethite	4.7 %
psilomelane s.l.	3.1 %
skutterudite	1.0 %
annabergite	22.6 %
erythrite	8.8 %
gypsum	40.4 %
residue	1.1 %

100.6 %

33 Hematite

Three types of genesis of hematite can be distinguished. These comprise:

- hematite as dehydration product of goethite (mentioned in paragr. 31)
- martitization of magnetite (mentioned in paragr. 30)
- hydrothermal

The latter type of hematite is widespread in the Inner Zone and it also occurs beyond the areas of sulphide or siderite mineralization. The hematite veins that are devoid of other ore minerals (Premol, Pic de Cabotte, Perrière, Arbarétan), have not been investigated in detail, since they possibly have no relation to the subject of study. Where occurring in carbonate-mineralized veins, hematite is often associated with barite (Roche Moutas, Crop, Fruithiers, Montgilbert, Les Gorges and Bonvillard) or quartz (Troix Laux, Rochefort, Tavernes). Without exception, hematite constitutes the latest phase of mineralization in this paragenesis. Chemically, hematite displays little variation. The Ti-contents vary between 0.2% (Prémol, Tavernes, Arbarétan and St. Charles) and 0.04% (Les Essarts, Perrière and Grande Roche). A pure hematite sample is difficult to prepare, because of frequent magnetitization, the Outer Zone's hematite deposits excepted (Rochefort, Tavernes). The transformation of hematite into magnetite takes place in two ways:

- either hematite is pseudomorphosed (St. Charles, fig. 52)
- or it is replaced by a porphyroblastic growth of euhedral magnetite (Les Essarts, fig. 53)

Magnetite pseudomorphs after hematite from the Dauphiné region have often been wrongly determined as ilmenite, due to the lack of a red streak, and because of similar colours. Hematite forms tabular crystals, of all sizes. Hematite of Tavernes forms "folded" aggregates of rather coarse crystal flakes (fig. 54). The processes that have led to this conspicuous fabric are not known. Mechanical folding can be excluded.

34 Ilmenite

Many specimens from Dauphiné labelled "ilmenite" or "crichtonite" have been shown to be magnetite pseudomorphs after hematite. Actually, only one occurrence of ilmenite has been

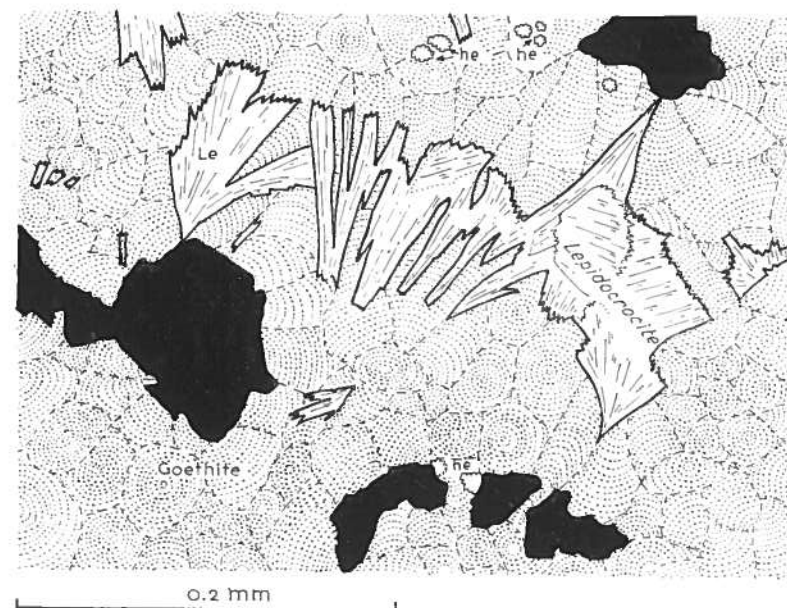


Fig. 51. Sheaf-like aggregates of lepidocrocite cut across botryoidally textured goethite (he = hematite). Rochefort.

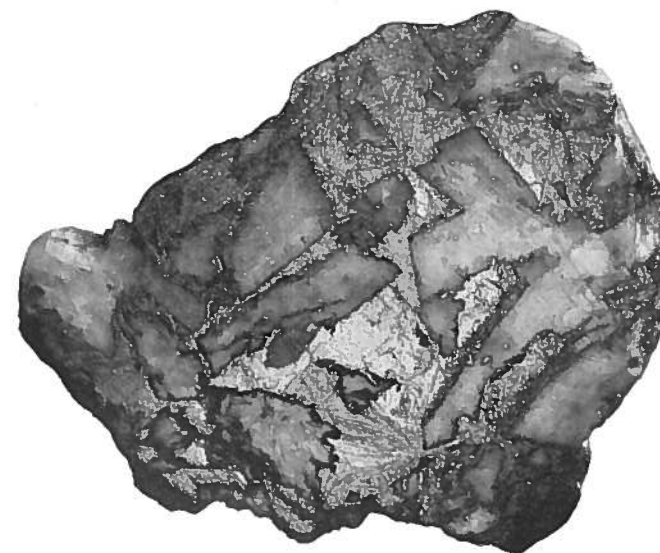


Fig. 52. Pseudomorphs of magnetite (high reflect.) after tabular hematite, filling the ankerite interstices (low reflect.). St. Charles, Allemont, 2 x.

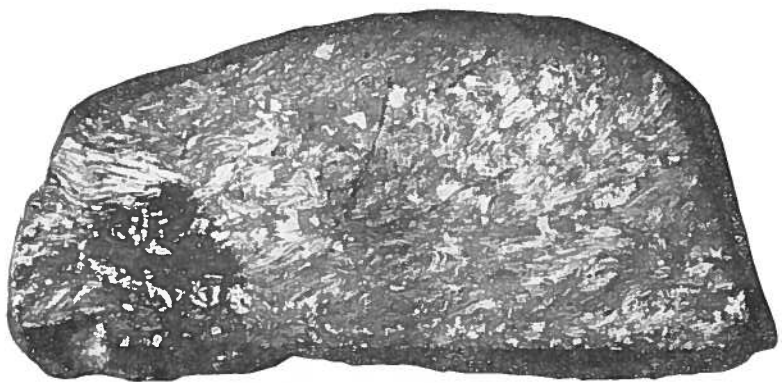


Fig. 53. Flakes of hematite embedded in calcite are replaced by euhedral magnetite, as shown by the etched part, where only magnetite has retained its reflectivity. Les Essarts, 2 x.



Fig. 54. "Folded" crystals of hematite. Tavernes, 3 x.

noticed. It comes from Chalanches in a small vein mineralized by chalcopryrite, pyrrhotite and ilmenite. The latter is older than the sulphides and is presumably related to the amphibolitic wall rock and possibly has nothing to do with the Co-Ni-Ag ores. This ilmenite has a flaky habit ("crichtonite").

35 Lepidocrocite

The high level outcrops of the Malpouchié, Trois Laux and Rochefort siderite veins yield very fine specimen of lepidocrocite. The crystallization conditions that seem to be favourable for lepidocrocite rather than for goethite are not known. The only thing that can be said is the occurrence of lepidocrocite in botryoidally shaped dehydrated iron-gels incrustating siderite, a feature that the three outcrops have in common.

The relation between goethite and lepidocrocite is such as to suggest a younger age of lepidocrocite the latter filling in fissures and other openings in the boxwork of goethite (fig. 51). Lepidocrocite is easy to recognize because of its flaky habit, its strong bireflectance and the sheaf-like texture.

36 Magnetite

Magnetite is confined to the Inner Zone of the Belledonne. Although it is widespread, yet, there are few deposits where magnetite makes up an original constituent: Roche Noire, Malpouchié, St. Charles; in all other deposits it has been formed by the transformation of hematite. The magnetite of Roche Noire et al. results from replacement of siderite by stilpnomelane and chlorite, in the process of which the remaining iron crystallizes as magnetite (fig. 63).

The magnetite porphyroblasts and pseudomorphs after hematite have been described with hematite. Chemically, magnetite does not depart from hematite, the Ti-percentages are of the same order of magnitude (0.2% Arbarétan to 0.03% Perrière). Only the newly generated magnetites of Roche Noire and Malpouchié, display higher Ti-percentages (0.4 to 0.8% respectively).

Magnetite from Arbarétan replaces hematites but, in turn, is replaced by hematite (martitization, fig. 55).

On analogy to the paragenesis of St. Charles, where magnetite of the stilpnomelane-chlorite suite pseudomorphoses hematite, the magnetitization is attributed to the younger mineralization phase. In the St. Charles deposit magnetitization is complete with hematite occurring in the calcite interstices, only hematite embedded in calcite or ankerite has been left unaffected (fig. 52).

37 Marcasite

Marcasite has only been noticed as secondary product of pyrrhotite and argentopyrite. Both are equally replaced by marcasite and pyrite. The alteration is accompanied by the development of typical birds-eye structures (Ramdohr, 1960).

38 Millerite

Millerite is a secondary product from the contact zone between siderite and chalcopyrite. In both localities, where it has been met (La Chevrette, La Fayolle), siderite replaces chalcopyrite and has been altered supergenely into goethite (fig. 56). Thus it is not known whether millerite results from alteration of siderite, or from replacement of chalcopyrite. The latter possibility seems most likely, since alteration of siderite is very common, and millerite has only been observed in direct contact with chalcopyrite. The millerite crystals are small and of irregular outlines. The typical fibrous habit has not been noticed.

39 Niccolite and breithauptite

Niccolite and breithauptite from Chalanches have been described by Ramdohr (1960) to occur in myrmekitic intergrowths, both minerals possibly being a decay product of arite, a high temperature solid solution of NiAs and NiSb.

Niccolite forms arborescent structures, which are incrustated by skutterudite. Later calcite selectively replaced the niccolite, leaving behind wreaths of skutterudite. Such reactions and parageneses are very common with the Co-Ni-Bi-deposits and have been described manifold.

40 Pentlandite

Pentlandite is only known from the Argentine pyrrhotite deposit, where it occurs as small spindle-shaped inclusions in pyrrhotite. This assemblage points to a catathermal genesis (Kullerud, 1956), a conclusion that agrees with the high Bi-content of Argentine's galena. The Argentine deposit is situated almost within the Belledonne's main granite (Sept-Laux-Epierre).

41 Polybasite

Polybasite is a rare silver-mineral, hitherto unknown from Chalanches. The present author was somewhat puzzled with its microscopical identification, since the normally occurring internal reflections could only be observed with difficulty, and its light-etching was obviously due to tiny argentite inclusions, and therefore did not constitute a property of polybasite itself. An X-ray diagram ascertained the determination, the lattice spacings being equal to those of polybasite s.s. according to Peacock and Berry (1937).

The faint internal reflections may be attributed to the Cu-content of polybasite (Ramdohr, 1960), being 5.4 wt. % Cu, which is a remarkably high figure. Polybasite is speckled by numerous disseminated spots of argentite (only visible shortly after polishing), and veined by argentite and native silver.

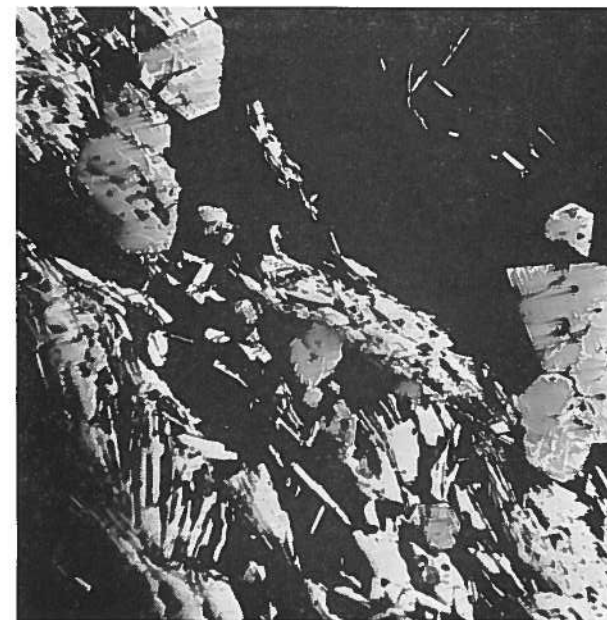


Fig. 55. Octahedrons of magnetite replace tabular hematite (highest refl.). Note martitisation of magnetite, 30 x.

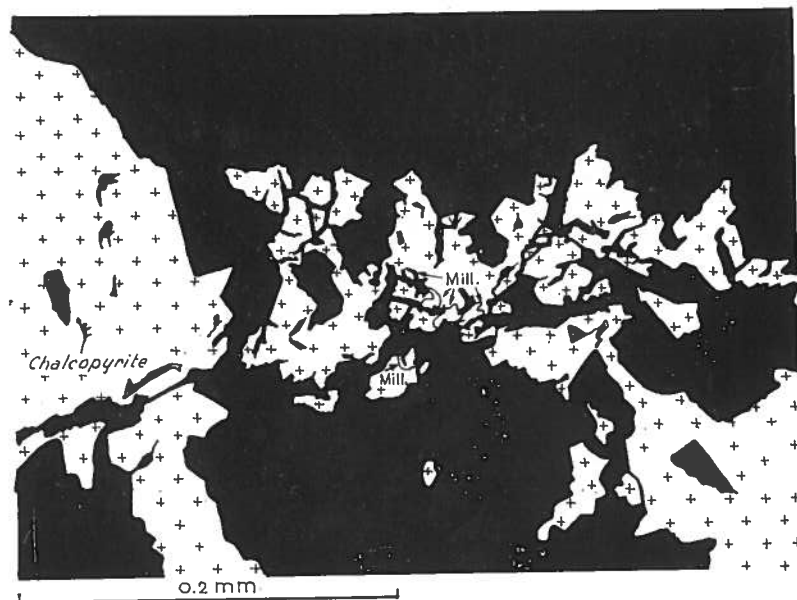


Fig. 56. Replacement of chalcopyrite by siderite (black) results into the formation of small millerite (mill.) crystals along the replacement borders. La Chevette.

42 Pyrargyrite

Pyrargyrite is one of the main silver-bearing minerals at Chalanches. It is replaced and veined by argentite and native silver. Polybasite may be formed as a reaction product between pyrargyrite and argentite. Veinlets of pyrargyrite belong to one of the youngest mineralization phases, as they project into calcite II and may even offset the latter's twin-lamellae. The pyrargyrite veinlets following the cleavage-planes of calcite also have acted as channelways for still younger polybasite, argentite and native silver.

43 Pyrolusite

Pyrolusite occupies a similar position in the supergene alteration process of manganese-oxides, as does hematite in the iron-cycle, both constituting an end stage in the weathering of siderite. Concurrent to hematite, the crystal sizes of the secondarily formed pyrolusite are exceedingly small (a few microns). The creamy colour, high hardness and distinct bireflectance serve to distinguish pyrolusite.

44 Pyrrhotite

Pyrrhotite known from the Chalanches, Le Char (Esserts-Blay) and Argentine deposits, constitutes one of the earliest minerals of the older paragenesis. Its occurrence bears interest since it permits a correlation between the high-temperature deposits of Argentine (high Bi-content), Esserts-Blay (FeS-rich sphalerite), and the Chalanches deposit, which does not provide conclusive evidence for the mesothermal nature (yellow sphalerite, low Bi-content), although the Co-Ni-Ag-Bi association is generally believed to represent a mesothermal ore suite. In the deposits mentioned pyrrhotite is accompanied by arsenopyrite and chalcopyrite. Its relation to chalcopyrite is so intimate that both may be of equal genesis. Comparable pyrrhotite occurrences bearing relation to the ultra-basic igneous rocks have not been found.

45 Quartz

The fluid inclusions of quartz have been the main object of this study. Interesting conclusions about age and physical condition of the mineralizations have been derived from them. Type of fabric and grain-size are mentioned in the table dealing with the parageneses of the ore districts. As has been mentioned in par. 40 of part I, the quartz inclusions are also useful to recognize a certain quartz phase. In the Chevette deposit, for instance, quartz occurs both as veinlets in siderite and as incrustations around wall rock fragments, building the so called cockade structures, fig. 57. Quartz I, forming part of the cockade structure possesses inclusions of a type definitely different from those of the veinlets (quartz II). Similar cockade ores have been described by Kutina (1957). He suggests

that the innermost quartz rims should be interpreted as a younger formation since the siderite cutting quartz veins reach to the cockade-quartz. This statement, however, needs proof of identity between both types of quartz, which proof can only be furnished by the inclusions of either type.

46 Safflorite and rammelsbergite

Safflorite has been identified among the Co-Ni ores of Chalanches, where it forms arborescent structures around bismuth, a texture that is very typical for the Co-Ni-Bi suite. Safflorite shows star-shaped (cyclic) twinning. According to Ramdohr (1960) rammelsbergite should also occur at Chalanches.

47 Siderite

The author owes a great deal of information about the genesis of the Belledonne metalliferous province to the omni-presence of siderite, which enables a correlation between all ore deposits to be made. The great value of siderite lies in the feature that its chemical composition is hardly susceptible to local recrystallization. There are many examples to prove this: Les Halles; Grande Chambre; Lac Crop; Le Merle and St. Georges. In these deposits dislocations have caused partial mylonitization of the siderite. As a result of its ready recrystallization ability the fine grained fabric has been restored to a coarser one, however without change of the Fe/Mn ratios. This ratio is not even susceptible to supergene alteration, as far as it concerns an alteration to goethite. Hematitization of goethite may bring on an essential change. Entrapment by quartz, which caused such conspicuous alteration of the chemistry of the sulphide minerals, has not affected the chemical composition of siderite.

Chemically, three groups can be discerned:

- siderites of the Inner Zone and Aiguebelle region (Fe/Mn ratio averages: 11)
- siderites of the older paragenesis of the Allevard region (Fe/Mn ratio averages: 22)
- siderites of the younger paragenesis of the Allevard region (Fe/Mn ratio averages: 40)

The Vizille region is somewhat aberrant, since the siderites comparable to the older ones of Allevard have higher Fe/Mn ratios, being in the order of 32, while those of the younger siderites are proportionally increased, being approximately 60.

Apparently a certain shift of composition occurs within one type. For instance the Chevrette, St. Hugon and Prodin siderites, geologically belonging to the Aiguebelle region, but occurring very close to the Allevard region, have Fe/Mn ratios that are similar to those of the older Allevard suite (viz: 18). In the Vizille region, where both Allevard and Aiguebelle type deposits occur, respectively west and east of the Carboniferous syncline of Mont Jean, the chemical distinction between both siderite types has vanished. Moreover, the points representing the analyses of Aiguebelle and Allemont siderites in a diagram (fig. 94) express a certain trend of increasing Mn- and

	1 PIERRE PLATE siderite I	1 PIERRE PLATE siderite II	2 ST. CHARLES siderite I altered	2 ST. CHARLES siderite II ank. contam.	3 siderite altered	4 GRANDE FOSSE siderite initial alter.	5 GRANDE COMBE siderite initial alter.
FeO	46.46	47.30	4.20	33.84	--	34.84	29.44
MnO	1.58	1.28	0.94	0.94	0.69	1.03	0.71
MgO	7.59	7.66	0.59	11.78	0.99	10.42	9.88
CaO	0.53	0.47	0.35	3.83	0.30	0.56	4.32
Fe ₂ O ₃	2.23	1.06	34.24	10.09	38.86	16.52	21.94
CO ₂	34.48	34.81	trace	32.42	1.24	28.60	29.56
H ₂ O	2.28	1.89	3.94	2.04	5.10	3.44	3.00
res.	5.26	6.16	56.26	5.32	52.74	5.34	1.62
	100.41	100.63	100.52	100.26	99.92	100.75	100.47

	7 MONT JEAN siderite I	8 LE VENT siderite anker contam.	8 LE VENT siderite advanced alter.	9 LES HALLES siderite low level	9 LES HALLES siderite high level	10 OLIVER siderite	11 MONT CHAFFREY siderite
FeO	30.98	37.40	13.45	38.82	39.42	38.04	34.06
MnO	1.07	0.83	1.18	0.58	0.64	0.80	0.56
MgO	5.73	12.48	5.48	12.51	12.63	12.80	11.99
CaO	0.68	4.23	0.25	0.42	0.30	0.32	0.39
Fe ₂ O ₃	2.23	2.79	63.13	0.60	6.26	3.14	3.63
CO ₂	25.36	38.00	8.82	35.32	36.64	38.80	32.38
H ₂ O	2.00	0.70	7.40	1.00	0.90	1.60	1.35
res.	31.18	3.92	0.62	10.95	4.30	7.50	15.80
	99.23	100.35	100.33	100.20	100.09	101.00	99.86

	11 MONT CHAFFREY siderite compl. alter.	12 LE PARC siderite	13 LE PARC siderite	16 GRANDE CHAMBRE siderite	16 GRANDE CHAMBRE siderite	17 LE SAPEY siderite Fe-oxyl. contam.	17 LE SAPEY siderite Fe-oxyl. contam.
FeO	--	37.60	37.62	39.84	30.60	22.26	22.20
MnO	1.20	1.21	1.08	1.50	1.10	0.90	0.81
MgO	trace	9.16	9.99	6.84	5.25	5.02	5.42
CaO	--	0.58	0.60	0.66	0.51	0.62	0.59
Fe ₂ O ₃	75.74	7.40	4.45	4.40	2.58	11.68	10.48
CO ₂	--	30.52	31.44	30.56	22.75	18.90	19.36
H ₂ O	7.60	1.31	1.69	1.16	1.27	2.56	2.76
res.	16.20	12.06	12.40	14.66	35.53	37.12	37.52
	100.74	99.84	99.27	99.62	99.59	99.06	99.14

	18 LES RUINES siderite	21 LA FAYOLLE siderite partial alter.	30 ROCHE NOIRE siderite compl. alter.	30 ROCHE NOIRE siderite partial alter.	31 BEAUREGARD siderite compl. alter.	31 BEAUREGARD siderite compl. alter.	32 MALPOURCHÉ siderite initial alter.
FeO	26.66	23.84	--	25.76	--	--	37.56
MnO	1.70	1.24	7.17	3.90	4.58	7.28	7.15
MgO	6.18	4.14	1.31	2.25	1.27	--	4.97
CaO	0.48	1.04	0.12	--	--	--	0.60
Fe ₂ O ₃	0.80	39.80	72.01	23.62	79.90	80.76	15.12
CO ₂	22.84	22.12	--	18.40	--	--	28.50
H ₂ O	1.78	5.89	8.38	5.26	7.28	9.95	2.75
res.	40.20	2.40	11.14	20.68	6.82	1.90	3.34
	99.64	100.47	100.13	99.87	99.85	99.89	99.99

	32 MALPOURCHIÉ siderite partial. alter.	33 TROIS LAUX siderite calcite contam.	37 LAC CROP siderite fine grained	37 LAC CROP siderite coarse grained	41 BOUT DU MONDE siderite anker. contam.	41 BOUT DU MONDE siderite	42 ALLEVARD siderite anker. contam.
FeO	32.74	32.12	40.46	38.36	48.12	48.86	14.14
MnO	6.37	5.06	4.67	4.32	2.40	1.41	0.38
MgO	2.51	4.32	4.67	4.51	4.70	7.08	6.38
CaO	--	4.71	0.36	0.11	0.46	0.41	6.73
Fe ₂ O ₃	25.78	23.14	13.78	9.34	7.97	7.38	2.40
CO ₂	26.17	27.48	29.00	27.90	32.26	30.16	18.64
H ₂ O	4.72	2.82	2.03	2.60	0.51	2.07	1.84
res.	1.04	0.22	5.58	13.78	3.56	2.56	48.68
	99.33	99.87	100.55	100.92	99.98	99.93	99.19

	43 RAFOUR siderite compl. alter.	44 ENVERS siderite initial. alter.	45 ST. JOSEPH siderite compl. alter.	46 REAGOUT siderite compl. alter.	47 ST. JACQUES siderite partial. alter.	48 GROS CHÊNE siderite partial. alter.	49 GRANDE TAILLÉE siderite initial. alter.
FeO	--	44.88	--	--	41.18	21.54	42.00
MnO	1.76	2.13	1.77	1.24	2.64	1.75	2.48
MgO	0.87	5.14	0.52	0.70	4.70	4.29	3.72
CaO	--	0.53	--	--	0.58	0.29	0.70
Fe ₂ O ₃	76.94	7.18	74.50	58.30	17.76	28.70	11.90
CO ₂	--	32.40	--	--	27.70	15.14	28.90
H ₂ O	12.62	1.22	9.36	7.46	2.12	4.74	1.87
res.	8.58	6.30	13.80	33.14	2.62	22.68	9.42
	100.77	99.78	99.95	100.84	99.30	99.13	100.99

	50 TILLERAY siderite compl. altered	52 CLAVETTE siderite compl. altered	53 MALATRAIT siderite compl. altered	53 MALATRAIT siderite compl. altered	54 RAVOIRE siderite partial. altered	54 RAVOIRE siderite	54 RAVOIRE siderite
FeO	--	--	2.08	--	28.02	46.50	49.14
MnO	1.27	3.06	1.94	1.76	2.96	2.50	2.82
MgO	--	0.96	--	0.83	3.70	5.46	6.06
CaO	--	--	--	--	0.15	0.49	0.50
Fe ₂ O ₃	79.76	80.02	79.66	82.16	38.64	7.52	2.77
CO ₂	--	0.90	0.43	--	19.68	31.40	33.87
H ₂ O	9.52	10.20	12.22	11.88	4.94	1.36	0.80
res.	10.40	4.40	3.17	2.56	1.56	5.20	3.88
	100.95	100.54	99.50	99.19	99.65	100.43	99.79

	55 ST SOPHIE siderite initial. altered	56 PANISSIÈRE siderite comp. altered	57 ETELLIER siderite	58 CUCHET siderite	59 ESPERANCE siderite	60 ROSSIGNON siderite	61 MARAMEILLE siderite alter into hemat
FeO	38.18	--	41.24	35.96	44.46	39.60	0.43
MnO	1.84	1.05	1.20	1.16	2.39	1.10	0.60
MgO	4.24	0.62	10.46	8.04	3.44	9.94	--
CaO	0.53	0.26	0.44	0.42	0.71	0.38	0.05
Fe ₂ O ₃	14.84	43.64	5.98	4.86	8.50	8.26	35.22
CO ₂	28.22	--	33.60	30.40	30.68	32.66	--
H ₂ O	2.47	6.70	0.96	1.20	1.91	1.48	5.00
res.	9.38	47.78	6.52	18.52	7.78	7.23	58.62
	99.70	100.05	100.40	100.56	99.87	100.65	99.92

	62 DU ROCHER siderite alter. into hemat.	64 COMBE NOIR siderite	65 GANGRETTE siderite compl. altered	66 PILLIARD siderite	67 CABOT siderite	67 CABOT siderite	67 CABOT siderite
FeO	--	46.76	--	49.40	48.97	49.61	49.33
MnO	2.80	2.41	2.00	2.58	2.09	2.03	2.10
MgO	--	4.94	--	5.87	4.60	4.61	4.68
CaO	--	1.27	--	0.70	0.51	0.52	0.58
Fe ₂ O ₃	93.02	4.42	53.16	4.30	2.85	0.99	2.05
CO ₂	--	23.60	--	34.58	34.25	34.84	34.30
H ₂ O	1.00	1.62	8.09	0.94	0.20	0.20	0.19
res.	3.60	5.34	37.60	1.28	6.02	6.48	6.00
	100.42	100.36	100.85	99.65	99.49	99.28	99.23

	67 CABOT siderite	68 FORTUNE siderite partial. altered	69 ST. ANDRÉ siderite partial. altered	70 POMINE siderite compl. altered	71 TAILLAT RIVES siderite	72 TAILLAT MAILLAT siderite coarse-grained	72 TAILLAT MAILLAT siderite fine-grained
FeO	49.15	37.12	25.10	--	40.64	42.79	39.68
MnO	1.97	2.84	2.81	2.21	2.21	1.28	1.35
MgO	4.56	4.55	3.89	0.38	7.04	11.42	8.92
CaO	0.49	0.49	0.43	--	5.01	0.50	0.35
Fe ₂ O ₃	1.57	21.54	40.64	68.84	4.60	2.49	2.72
CO ₂	34.91	24.60	16.54	--	33.20	35.20	30.92
H ₂ O	0.26	2.68	6.18	9.44	1.18	1.33	1.37
res.	6.00	5.58	4.26	19.80	6.70	4.90	14.36
	99.35	99.40	99.85	100.67	100.58	99.91	99.67

	74 ROCHFORD siderite compl. altered	74 ROCHFORD siderite compl. altered	75 TAVERNES siderite compl. altered	76 LA FEUILLETTE siderite	77 PIOULAZ siderite	78 GENIVELLE siderite	79 PATUREL siderite compl. altered
FeO	--	--	0.12	42.16	27.84	26.74	--
MnO	0.84	1.51	0.46	1.18	0.92	0.79	0.96
MgO	0.22	0.62	0.14	10.72	6.38	8.10	0.34
CaO	0.11	--	0.04	0.31	0.35	0.26	0.19
Fe ₂ O ₃	35.12	65.20	21.24	6.00	4.64	7.76	81.90
CO ₂	--	--	0.14	36.08	22.44	22.48	0.53
H ₂ O	7.50	11.76	3.04	1.26	1.85	2.20	10.90
res.	55.24	21.80	73.98	2.44	35.00	31.62	4.62
	99.03	100.89	99.16	100.15	99.42	99.95	99.44

	80 LE MERLE siderite coarse grained	80 LE MERLE siderite fine grained	81 GIRODET siderite compl. altered	82 LES VIOLETTES siderite compl. altered	84 LE COUDRE siderite compl. altered	85 PIERRE HERSE siderite	85 PIERRE HERSE siderite
FeO	42.42	41.06	2.20	--	--	40.40	43.50
MnO	0.67	1.00	1.39	2.16	0.84	1.56	1.45
MgO	13.76	13.14	0.07	0.74	0.38	11.01	10.68
CaO	0.45	0.42	--	--	--	0.52	0.48
Fe ₂ O ₃	1.14	9.90	72.68	83.96	62.86	5.64	4.08
CO ₂	38.84	34.01	--	--	--	34.48	37.62
H ₂ O	1.35	1.35	12.52	9.64	8.44	1.16	1.21
res.	0.48	--	12.00	4.76	28.40	5.44	0.30
	99.11	100.88	100.86	101.26	100.92	100.21	99.32

	86 MERCARET siderite compl. altered	86 MERCARET siderite partial altered	86 MERCARET siderite compl. altered	87 LAC DE LA JASSE siderite CO ₂ calculated	88 MOLLIET siderite	91 LA CHEVRETTE siderite initial altered	91 LA CHEVRETTE siderite
FeO	--	16.22	--	43.98	28.70	41.40	45.82
MnO	1.00	1.18	0.62	1.72	0.50	3.18	2.74
MgO	0.33	4.70	0.17	9.87	10.54	3.59	5.38
CaO	0.32	0.39	0.13	0.50	0.57	0.46	0.42
Fe ₂ O ₃	39.10	33.94	24.12	2.86	2.39	17.02	2.87
CO ₂	0.44	14.08	0.09	35.00	26.24	29.00	33.64
H ₂ O	6.42	5.67	3.23	0.82	1.29	2.78	0.84
res.	51.94	24.50	71.06	5.96	29.02	2.08	8.88
	99.55	100.68	99.42	100.71	99.41	99.51	100.61

	93 REMOUD siderite initial altered	94 PRODIN siderite	96 PERRIERE siderite initial altered	96 PERRIERE siderite compl. altered	97 FRUITHIERS siderite anker adm.	105 ST. GEORGES DES H. siderite coarse grained initial altered	105 ST. GEORGES DES H. siderite fine grained
FeO	25.66	39.92	23.22	--	35.10	29.20	18.82
MnO	1.01	3.22	0.64	0.56	3.68	5.00	3.91
MgO	5.56	3.62	5.12	0.33	3.77	2.44	0.89
CaO	0.49	0.81	0.40	0.10	2.88	0.23	0.98
Fe ₂ O ₃	15.32	5.58	9.62	45.60	9.65	24.24	8.73
CO ₂	19.30	27.50	18.04	--	28.64	20.58	16.16
H ₂ O	2.90	2.39	2.60	6.40	1.93	3.98	2.13
res.	29.42	16.11	39.72	47.00	14.58	13.62	47.50
	99.66	99.15	99.36	99.99	100.23	99.29	99.12

	106 MONTGILBERT siderite compl alter.	107 LES GORGES siderite	108 BONVILLARD siderite	111 ESSERT-BLAY siderite partial alter.	49 GRANDE TAILLÉE siderite initial. alter.
FeO	--	40.83	43.17	10.34	37.06
MnO	4.60	4.71	7.44	5.44	1.49
MgO	0.82	3.58	5.94	3.94	5.76
CaO	0.52	2.19	0.48	0.03	0.26
Fe ₂ O ₃	33.60	16.75	4.60	43.06	15.70
CO ₂	1.92	28.00	33.30	5.23	27.40
H ₂ O	7.34	2.37	1.40	6.95	2.67
res.	50.28	1.08	3.98	24.86	8.98
	99.08	99.51	100.31	99.85	99.32

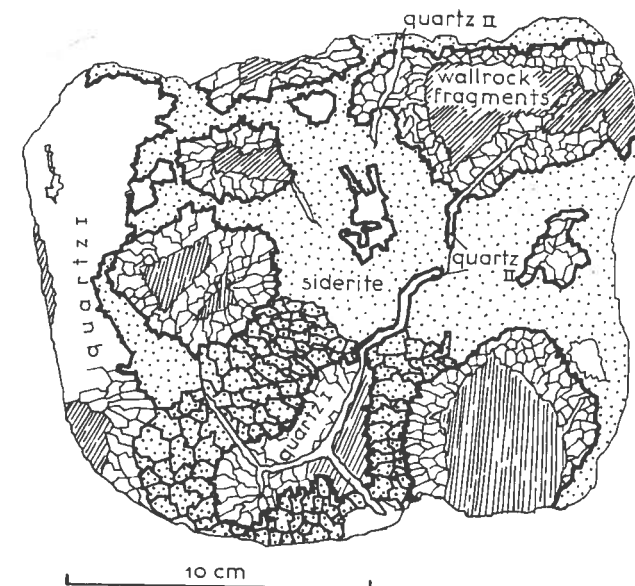


Fig. 57. Cockade ore. Concentric rings of quartz I around wall rock fragments, succeeded by intricately intergrown siderite. Both older formations are cut across by veins of quartz II. La Chevrette.



Fig. 58. Detail of siderite of La Chevrette, intricately intergrown fabric of fusiform crystals. La Chevrette, 2 x.



Fig. 59. Large rhombohedral crystals of siderite belonging to the younger mineralization. Le Merle, $\frac{2}{3}$ x.

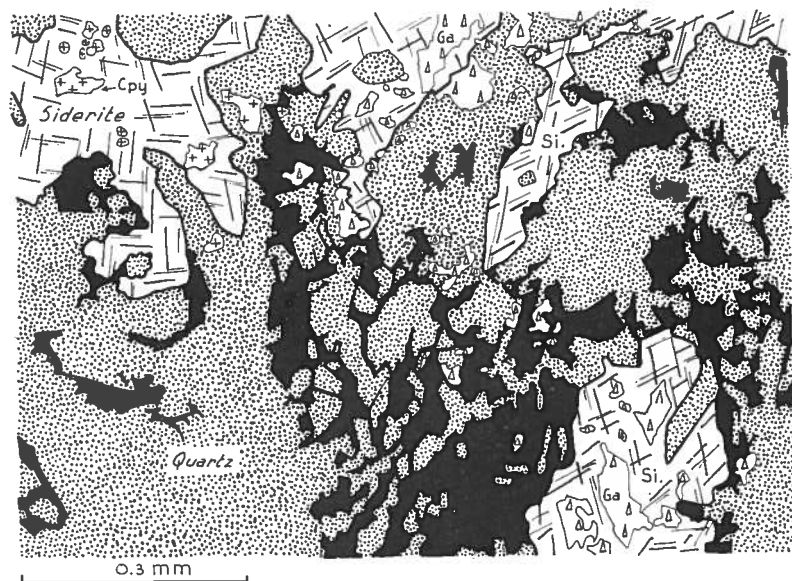


Fig. 60. Disperse sideritisation of walk rock fragments enclosed in the quartz vein of Sapey. Siderite replaces galena (Ga.) and chalcopyrite (Cpy.).

decreasing Mg-content. This trend joins that of the older Allevard suite (fig. 85). Here, the trendline is particularly clear, mainly because all analyses that have been affected to any extent by alteration have been discarded, a selection that could not rigidly be applied to the Aiguebelle analyses because of scarcity of material. Another feature that the Aiguebelle, Allemont and older Allevard and Vizille siderites have in common is the parallel texture of the elongate, fusiform crystals (fig. 58 and 67), which is so conspicuous that the older Mn-rich siderite is easy to recognize as such because of its fabric. This type corresponds approximately to the Rives siderite of Gueymard (1844), although he used this name only to denominate siderites of a finer grain size than that of the coarse grained Maillat-siderite. Hence we may safely assume that the differences between both the older Allevard-Vizille and the Aiguebelle-Allemont groups only represent the normal differentiation course of ore bodies in space.

As shown by the diagrams (fig. 70 and 85) there exists a large composition gap between the groups just mentioned and the younger siderites of Allevard and Vizille. The sole analyses that have intermediate values (Pierre Plate, Mont Jean, Les Ruines, Bout du Monde, Grande Taillée and Taillat) are from localities where both older and younger mineralizations occur in the same vein or very close to each other in such a manner that hybrid genesis may be supposed. Moreover it is remarkable that the composition gap between the younger and older Allevard siderites on the one hand and the younger and older Vizille siderites on the other are of the same order of magnitude. The younger siderites are not only distinguished by their chemistry but also by their fabric, which is an isotropic one, made up of equi-dimensional grains (fig. 59).

Apparently the younger siderite represents an individual mineralization phase, before or during which the tectonic conditions have changed. As will be shown the younger siderite is a product of rejuvenation of an older one, which means the only process that counts for the distinct chemical relation between older and younger siderites within one certain area, the Mn-content having been diminished by the same factor with all rejuvenated siderites. Other elements that have been analyzed for appear not to be as useful as manganese for the genetical interpretation of siderite. The titanium-content, for instance, did not show any significant relation with regard to temperature, location or fabric. The values ranging between 4 and 87 ppm, with a frequency maximum of 55 ppm. The siderite of Sapey is the sole one that departs from this range, having a Ti-content of 235 ppm. This is due to the nature of the mineralization, being a disperse sideritization of the country rock, whereby siderite preferably replaces rutile (fig. 60).

48 Silver

Silver, only known from Chalanches, occurs in two modes: either as the latest product of the silver-suite, or as arbitrarily shaped masses of descendent origin. Both have already been described, the former with the minerals to which it is associated (pyrargyrite, polybasite and argentite) and the

latter with other secondary products: annabergite, argentite and gypsum.

49 Skutterudite and smaltite

According to Ramdøhr (1960), Groth (1885) and Gueymard (1844) smaltite is one of the main minerals at Chalanches. Unfortunately, it only has been noted by the author from a supergenically altered vein, where its situation did not allow any observations about the paragenesis to be made.

50 Sphalerite

In addition to siderite and quartz, sphalerite is most informative about the physical conditions, under which it and the other minerals paragenetically related to it, have crystallized. The FeS-content of sphalerite is widely used in geological thermometry (Kullerud, 1953). However, its application is limited to those cases where equilibrium between ZnS and FeS exists, which may appear from the association of sphalerite with pyrrhotite or pyrite. Although this postulate is not fulfilled with the Belledonne sphalerites, we may yet refer to the black (>10 mol.% FeS) sphalerites from La Fayette, Fond de France, St. Hugon and Esserts-Blay as being of meso- to catathermal genesis, since the Kullerud-temperatures (300°-350°) only constitute minimum temperatures.

The FeS-content is very susceptible to recrystallization or entrapment of sphalerite by quartz, a low iron-content being the result. This process is clearly exemplified by the Sapey deposit, which because of spatial relationship and equal mineralogy is supposed to belong to the same mineralization period as the Fayette deposit, which is of proven high temperature genesis. The sphalerites of Sapey, however, have FeS contents that according to the mode of entrapment vary from 4.9 mol. % FeS for sphalerite occurring in the brecciated country rock fragment (fig. 66) to 2.5 mol. % FeS for sphalerite broken up by and embedded in quartz II (fig. 71). In this way the sphalerites of Prévieux, Perrelle, Fosse Guerre and Bonvillard have been depleted of iron. Apparently, the country rock prohibited a direct contact between sphalerite and quartz, thus preserving sphalerite for an almost total loss of iron.

The loss of iron is accompanied by exsolution of chalcopryrite. Sphalerites that still contain their FeS display only some very small exsolution drops, evenly scattered over the whole crystal. Exsolution that occurred under the influence of quartz or of later mineralization disrupting sphalerite produced a concentration of chalcopryrite exsolution drops concentrated alongside the younger mineral (Grande Chambre, Ravoire and many others). This phenomenon is a useful tool for establishing age relations, and may be added to the characteristics that serve to recognize mineralization sequences as listed in the textbooks of Edwards (1947) and Bastin (1950). This process proceeds by the increase of size of the exsolution drops and their agglomerations, such as exemplified by the sphalerite of Sapey occurring in the country rock fragments. The final stage of the

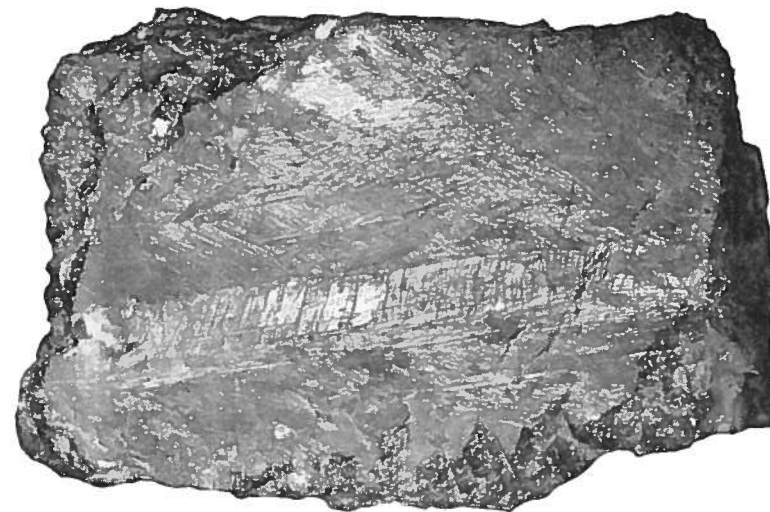


Fig. 61. Lamellar twinning of sphalerite as a result of deformation. Pierre Herse, 1 x.

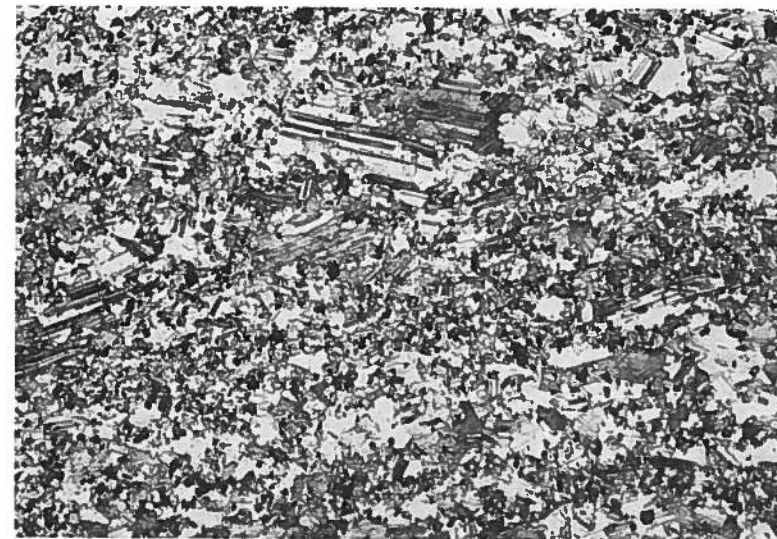


Fig. 62. Detail of figure 61, showing a fine grained recrystallization fabric of sphalerite, besides larger twinned crystals. Pierre Herse, 30 x.

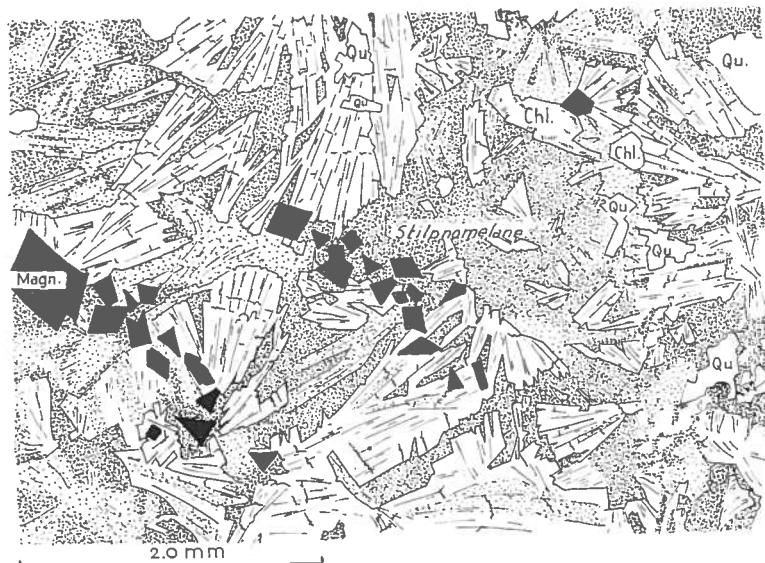


Fig. 63. Stilpnomelane (sheaf-like aggregates or basal sections), chlorite (Chl) and magnetite (Magn) as low grade metamorphic alteration products of siderite. Roche Noire.



Fig. 64. Arbitrarily shaped ullmannite (Ullm) crystals are confined to the sulphide-streaks of the La Fayolle vein. Note intergrowths of sphalerite (Sph) and chalcopyrite (Cpy) and exsolution drops of chalcopyrite (crosses) in sphalerite.

process means loss of all chalcopyrite, and of the greater part of the iron formerly incorporated.

Sphalerites that have been replaced during Alpine orogeny have FeS-contents varying from 0 to 0.5 mol. %. Their alpine emplacement appears from the Triassic or Liassic age of the wall rock (Laffrey-Peyerère-Longerolle) or its position on a fault of Alpine age (Vaujalaz of the Median Syncline).

Sphalerite possesses not such a ready recrystallization ability as galena or the carbonates, and provides fine examples of the stresses to which the ores have been subjected. (Bonvillard, fig. 96, 92 and 93). For instance, etching has revealed the sphalerite assemblage of Pierre Herse to be composed of large crystals (1-5 cm) that have been broken down into some larger pieces embedded in an extremely fine grained matrix (fig. 61 and 62).

Chemical composition of sphalerite:

	wt. % Fe	Mn	Cu	Co
16 Grande Chambre	4.24	0.009	0.07	0.02
17 Le Sapey (country rock embedded)	3.50	0.011	1.06	0.03
17 Le Sapey (quartz embedded)	1.30	0.004	-.	0.02
20 Longerolle-Peyerère	0.12	0.004	-.	0.001
Laffrey	0.27	0.008	0.09	0.002
Peuchagnard	0.23	0.002	-.	0.001
21 La Fayolle	6.50	0.016	0.98	0.10
23 Chalanches	3.34	0.146	not.det.	0.03
54 Ravoire	2.60	0.006	0.12	0.05
54 Ravoire	3.36	0.008	0.77	0.06
85 Pierre Herse	0.95	0.007	not.det.	0.05
90 Fond de France	6.20	0.042	0.18	0.06
92 St. Hugon	7.03	0.018	0.09	0.006
98 Malrocher	3.18	0.008	0.30	0.01
99 Prévieux	3.68	not.det.	not.det.	0.002
101 Fosse Guerre	1.96	0.007	0.12	0.007
102 Perrelle	2.50	0.013	1.60	0.003
108 Bonvillard	1.77	0.009	0.22	0.001
108 Bonvillard	1.40	0.011	0.23	0.001

51 Stilpnomelane

The occurrence of stilpnomelane as a product of low-grade metamorphism of the biotite-chlorite-muscovite-schists of the Inner Zone has been supposed by Kalsbeek (1962). Stilpnomelane of such paragenesis is regarded to be common in the western Alps. Its formation is attributed to epizonal metamorphism of Alpine age (E. Niggli, 1956, and Ellenberger, 1957).

The stilpnomelane occurrence found by the present author, however, is related to low-grade metamorphism of iron ores. This metamorphism may equally belong to Alpine orogeny, since the flakes are randomly oriented and do not show any sign of stress, such as broken or bent crystals.

Stilpnomelane and chlorite replace siderite. The chemical mechanism of this process will be mentioned in chapter II, in the section dealing with the mineralogy of the Allemont deposits.

Manganese has been incorporated in the same ratio to iron as is present in siderite. The greater part of the magnesium has been taken up by chlorite. The stilpnomelane produced in this way, does not depart chemically from the average ferric-stilpnomelane (Deer et al. 1962).

Stilpnomelane of Roche Noir:

SiO ₂	45.00	
Al ₂ O ₃	5.02	
Fe ₂ O ₃	28.85	
FeO	4.63	
TiO ₂	0.06	
MnO	2.35	
MgO	3.54	
CaO	0.25	
Na ₂ O	0.20	
K ₂ O	0.50	
P ₂ O ₅	0.10	(apatite)
H ₂ O	<u>9.37</u>	
	99.87	

Optical data:

N_{α} : 1.615, golden yellow
 N_{γ} : 1.695, dark brown

Stilpnomelane of similar composition has been described and analyzed by Hutton (1956) from epidote-chlorite schists in New Zealand.

Stilpnomelane of Roche Noire and Malpourchié forms large (up to 10 mm) thin plates of sheaf-like arrangement. The second cleavage, perpendicular to the perfect basal one, is distinct (fig. 63). Stilpnomelane alters into goethite.

52 Tetrahedrite

Tetrahedrite is of widespread occurrence in the Belledonne metalliferous province and is known from all kinds of deposits. Tetrahedrite has not been investigated geochemically. Thus, it is not known if its different paragenetical setting is reflected by its chemistry. A qualitative analysis has shown that apart from the common Cu and Sb, also Fe, Zn and Ag are present. The sole difference which has been noted between tetrahedrite of the older and younger mineralization suites, is its association with chalcopyrite, being intricately intergrown with chalcopyrite in the older paragenesis (fig. 90), a relation that is absent with chalcopyrite in the younger suite. In both instances tetrahedrite has been followed up by galena, but only in the case of recrystallization the reaction series tetrahedrite-bournotite-boulangerite-galena has been formed. Tetrahedrite is the common host of gersdorffite and ullmannite.

53 Ullmannite

Ullmannite has been noticed for the first time from the Belledonne Range by Guillemin and Levy (1957), who identified an isotropic, hard and silver-white mineral of high reflectivity from a core-sample of Petitchet (Fayolle) as ullmannite by

micro-chemical reactions on Ni and Sb. The present author was able to confirm this determination by X-ray analyses of ullmannite samples of La Fayolle, Sapey, Chevrette and Remoud. These are all deposits from the Outer Zone, in the area east of the Carboniferous synclines of Mont Jean and Grand Collet. In the Allevard region it has never been noticed. Apparently it only occurs in ore suites, that indicate a mesothermal genesis notwithstanding recrystallization.

Ullmannite is distinct from gersdorffite by its arbitrarily shaped crystals, sharply contrasting to the euhedral outlines of gersdorffite. The etching test with bromine, which is negative with ullmannite, may also serve as a mark of distinction.

PART III THE ORE DEPOSITS

CHAPTER I

ORE DEPOSITS OF THE VIZILLE REGION

The ore deposits are not equally distributed over the Belledonne Massif. Some areas are richly endowed with ores, whereas others are completely devoid of it. But, not only the distribution of the ores shows regional contrast, also their mineral contents display regional differences. Hence, certain ore districts can be distinguished.

As may be expected the limitations of such districts are geological ones. In the Belledonne, however, with its young and pronounced relief, the geological limitations have morphological and geographical consequences. One such a geologically and geographically defined area is the Vizille region.

1 Geographical setting and morphology

The Vizille ore district is situated in the SW part of the Belledonne Range and consists of the region east of Vizille, the most important town of this area.

The western border of the area is the NNE-SSW trending valley of Uriage and Vizille, located along the steep western slope of the Belledonne. From a geological point of view this valley represents the anomalous contact between the crystalline rocks and the Mesozoic sediments, the latter building up the border chain of the "Collines Liasiques" (Liassic hills).

The Median Syncline constitutes the eastern border. Its position is marked by the N-S trending valley of Séchilienne. Both boundaries intersect near Uriage.

South of Vizille the region is traversed by the E-W flowing Romanche river. The area south of the river belongs geographically to the La Mure district, but the outcrops of the same geological formations continue some three kilometres southward to the point where they are submerged under a thick Mesozoic cover and further on are denoted as the crystalline basement of the La Mure Dôme. Therefore, also some ore deposits south of the Romanche river will be drawn into consideration here.

The erosion that has modelled the Belledonne into its present state is assumed to have started after the sliding down of the Mesozoic cover into a westerly situated depression (Blanchard, 1941). The presence of an attached sedimentary cover, which is known to have possessed a thickness hardly greater than that of the present day, should be taken as an indication that erosion has begun only recently (Sarrot-Reynauld, 1961). This is also obvious from the fact that the western side has preserved its original steepness, the slope having hardly been attacked by streams.

The "Collines Liasiques" have retained their original

structural relief, the structural anticline being a topographic culmination. Though the mountains of the Belledonne reach altitudes of 3000 metres and, at a distance of only 7 kilometres, the great valley of Grésivaudan levels off at 220 metres, the friable sediments of the "Collines Liasiques" have hardly suffered erosion, being merely dissected by some transverse gorges.

The youthful nature of the morphology may be attributed to the fact (Blanchard, 1941, and Moret, 1952), that the Belledonne has only achieved its mountainous character in the later episodes of the Alpine orogeny (Upper Miocene). Even the formation of the great depression bordering the Belledonne (the Grésivaudan and the "Combe de Savoie") must have been older, since the uplift of the Outer Zone resulted in the gliding of its Mesozoic cover into this depression.

2 Historical notes on the ore deposits

Since antiquity the Vizille region has played a prominent part in the history of the Belledonne. Its situation near the gorge of the Romanche, the most important trade route between Trans-Alpine and Cis-Alpine Gaul, made Vizille a strategic point in the Roman era. An indication of the interest that the Romans took in the region are the public baths, which have recently been excavated near the springs of Uriage-les-Bains. The aqueducts and "thermae" are known to have been built during the reign of Augustus. These springs will be dealt with geologically in chapter III, the springs of Allevard-les-Bains being similar in chemical composition and geological setting.

There is no evidence that the ore deposits of this region were worked in antiquity. It is not until the fourteenth century, that any written account of the ores was made.

The first features of ore exploitation to be recorded are the hydraulic hammers, the so called "martinets", at Vaulnaveys and Vizille built in 1319 and 1341 respectively (Allix, 1917). In 1428, mention was made of a "martinet" at St. Pierre-de-Mésage and in 1593 of a forge at Vizille. A blast-furnace is known to have existed at Livet in 1662. The industrial development of the area must be attributed to the abundant water-power. Most of the raw materials used in the forges and blast-furnaces are likely to have been imported, for the output of the local ore deposits alone could not have justified all this activity.

It was not until the eighteenth century that mining of the ore deposits has been mentioned. The appearance of two roasting furnaces one at Vizille and another at Uriage, in the early part of this century is a reliable indication that there was mining on a somewhat larger scale, since roasting was always performed as close as possible to the mines, the transport being complicated at that time. It may be pointed out here that the siderite ore gains in iron content and loses considerably in weight upon calcination.

In this period the mining and smelting of iron was carried out by a company having its blast-furnace in St. Laurens-en-Royans (Drôme). In 1787 it was taken over by a company owning the St. Barthelemy and Articol blast-furnaces. This company mined iron ore near Vizille as well as lead, copper and zinc near

Séchilienne. Around 1800 all mining activities ceased.

In 1826, after coal-mining in the La Mure district had been developed on an industrial scale, a big blast-furnace was constructed by the "Société Anonyme des Fonderies de Vizille". This company also owned the lease of the mines. It gave iron mining a renewed period of activity. Base-metals, too, were mined occasionally.

After another period of idleness, the mines were taken over by the "Société des Hauts-Fournaux de Rioupéroux", which exploited the ores till 1865, the year in which the company decided to make no further use of the local minerals. Some years afterward the last mine was closed.

This state of inactivity has continued up to now, with the exception of the Les Ruines mine having been operated from 1911 to 1916. Many years have passed, too, since the fires of the blast-furnaces were extinguished for the last time.

Nowadays, the metallurgical tradition of the region is continued by electrochemical works, supplied with energy by the hydro-electric power stations along the Romanche, such as there are in: Livet, Rioupéroux, Gavet, Séchilienne, l'Isle de Montfalcon, St. Pierre de Mésage and Le Péage de Vizille.

3 Mining methods and exploitation data of the individual deposits

The mining-methods used in the exploitation of the Vizille ores were not very elaborate, mainly because of the short distance of the ore bodies to the surface. Other reasons why simple mining methods were sufficient may be sought in the shape of the ore bodies (viz: sheetlike with flat walls), in the nature of the ore (siderite is a rather friable mineral), and in the fairly constant grade of the ore. These features may explain why most mining operations could be performed by unexperienced workers such as farmers practising mining as their spare time occupation. The exploitation of the greater part of the ore bodies started as an open cutting, costeaning the vein downward. This has happened to the ores of St. Charles, Grande Fosse, St. Julie, Grand Combe, Le Vent, Les Halles, Oliver, the mines of Montchaffrey, St. Pierre de Mesage and Grande Chambre. These open cuts usually have a trench-like shape and can be of great depth, especially when the ore body is about vertical.

But not all the mines that show a deep open trench at the surface were worked by open cutting exclusively, many of them have been exploited in their lower parts by overhead stoping. These parts were made accessible by drifts (like Grande Combe and Grande Fosse) or by crosscuts (like St. Charles, Les Halles and Grande Chambre). A few ore bodies were not very well mineable by open cut methods and have been opened up by adits only, like Pierre Plate, where two adits at different levels are present, and the mine of Mont Jean, situated in the lower part of the vein of Le Vent. Only one mine in the Vizille region, Le Sapey, was provided with a shaft in addition to two tunnels.

The most modern exploitation is found at les Ruines, where in 1911 on the steep northern slope of the Romanche Valley a broad bench has been built up from the talus and the waste of a large adit. A cable way was constructed for the transport of men and material. The costly operation ceased in 1916 because of the low

grade of the ore.

4 Geological outlines

The geological outlines of the Belledonne have been recorded in the introduction. However, some details of the geology of the Vizille region will be described here because of their interest in relation to the ore deposits.

The ore deposits mainly occur in the crystalline rocks of the area. A few are met in the Mesozoic sediments. Hence, a brief description of the crystalline rocks and a review of the stratigraphy will be given below.

a. Outer Zone schists

The crystalline rocks of the area under discussion are part of the Outer Zone of the Belledonne, and consist mainly of sericite-chlorite-albite schists. Several names have been proposed for this series. Michel and Berthet (1958) in their study of the Romanche section designate them as the "Vizille Group" and think their original metamorphic grade to belong to the "Zone des Micaschistes Inférieur" of Jung and Rocques. The present epithermal character of the schists should have resulted from retrograde metamorphism and a sodium-metasomatism, causing the growth of albite porphyroblasts.

Sarrot Reynauld (1958) shares this opinion on the basis of observations made in the La Mure district, and suggests an Alpine age of the sodium metasomatism, since albite veins occur in the Upper Carboniferous. The observations of Tobi (1959) do not agree with this theory. They show, although one or more phases of retrograde metamorphism with subsequent migration of matter do have occurred, the albite-porphyroblasts to be contemporaneous with the original progressive metamorphism of the schists. His opinion is based on the presence of trains of minute rutile inclusions in the albite reflecting a pre-metamorphic micro-folding that later on has vanished and also on the actual occurrence of the albite-porphyroblasts in sericite-biotite schists that are absolutely unaffected by the retrograde metamorphism, whereas they lack in Inner Zone schists that show may signs of it.

It should be noted here, that Michel (1958) underrates the difference in metamorphic grade between the two Belledonne Zones by locating the main part of the Inner Zone rocks (designated as the "Séchilienne Group") also into the "Zone des Micaschistes Inférieur", since staurolite, garnet and cyanite are absolutely absent in the Outer Zone.

b. Upper Carboniferous

The Upper Carboniferous consists of conglomerates, phyllites and coal seams, and is of Westphalian-D and Stephanian-A age. In the La Mure district the carboniferous seams have given rise to an important coal mining industry. In the region under discussion the Upper Carboniferous coal never has been mined on an industrial scale, the seams being thin and disrupted by numerous dislocations.

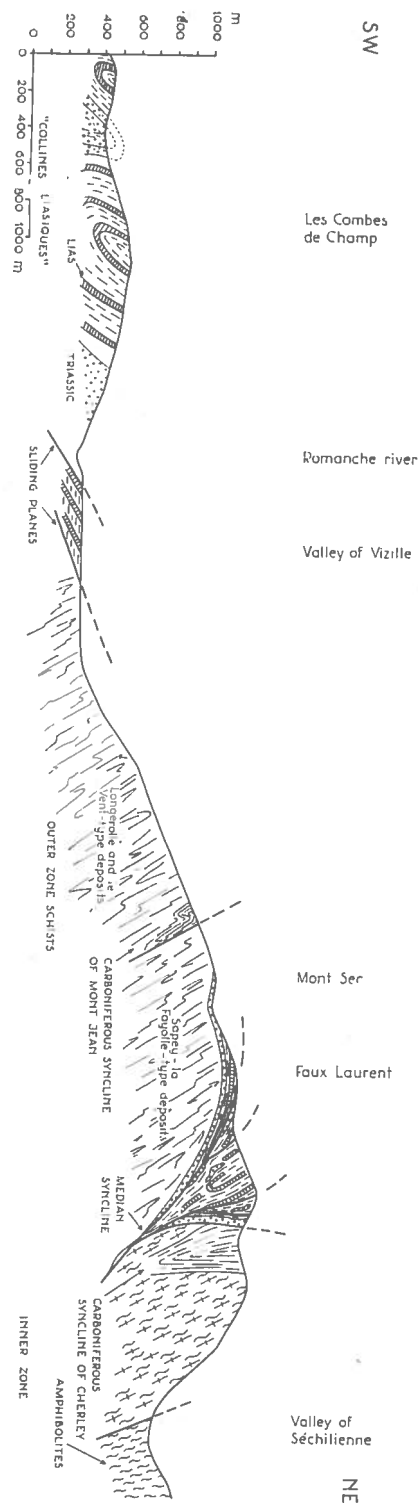


Fig. 65. Section through the Median Syncline and Carboniferous syncline of Mont Jean in the Vizille region, according to Moret (1952) and P. Lory (1948).



Fig. 66. Dispersely mineralized wall rock fragments have been disrupted by quartz I. Figure 60 represents a detail of such a mineralized wall rock fragment. Le Sapey, 1 x.



Fig. 67. Serratedly intergrown, fusiform siderite crystals, oriented perpendicularly to streaks (black) of wall rock. Grande Chambre, 1 x.

The Upper Carboniferous bears interest with regard to the ore deposits not so much as host rock as because it fixes the upper age limit of the main metamorphism of the crystalline rocks, and as much as it marks the fault plane bordering the compressed syncline of Mont Jean. Wherever the Triassic is lacking, the presence of Upper Carboniferous rocks as autochthonous sedimentary cover may indicate the proximity of the pre-Triassic peneplain.

c. Mesozoic sediments

The Mesozoic sediments are of Triassic and Liassic age. The Triassic comprises: anhydrite, gypsum beds, spilites, dolomites, cavernous limestones, the so called "cargneules". The Lias comprises limestones and calcareous schists.

d. Quaternary deposits

The Quaternary is made up of glacial deposits in the valley of Vaulnaveys and alluvial deposits in the bed of the Romanche river.

5 Structural geology

It has been shown that the limitations of the Vizille ore district coincide with a tectonically defined area. The nature of the faults bordering this area will be discussed.

a. Median Syncline

The Faux Laurent area shows a complicated exposure of the Lias and Triassic (fig. 65). The Mesozoic of its westernmost part is about horizontal, displays a normal stratigraphical order of its sediments, and hence, is thought to be an attached sedimentary cover. To the east this picture changes into a steeply dipping, intricately folded mass of Mesozoic sediments representing the Median Syncline. The latter is bordered on its eastern limb by a tightly compressed Upper Carboniferous Syncline.

A few kilometres north and south of this outcrop the whole complex pinches out, becoming merely a fault between the albite-sericite schists of the Outer Zone and the gneisses and amphibolites of the Inner Zone. Such a "pinch and swell" structure is characteristic for the Median Syncline. It is the result of strong compression exerted by the overthrust of the Inner Zone, which in combination with the lubricating Triassic gypsum caused the Mesozoic content of the Median Syncline to be squeezed out. In some places a pocket of gypsum or anhydrite is all that has been left (P. Lory, 1944).

b. Gravitational gliding and "Collines Liasiques"

The range of hills flanking the western slope of the Belledonne, and known as the "Collines Liasiques" has obtained its position as a result of the same agents that have deprived the Median Syncline of its sedimentary content. Part of the Liassic hills may even have been derived from the Median Syncline.

The main difference between both tectonic features is the nature of the motoric force to which the Lias owes its allochthonous setting, viz: compression versus gravitation. However, both forces have worked in the same direction and both belong to the Alpine orogeny.

c. The Upper Carboniferous syncline of Mont Jean and Montchaffrey

The Vizille ore district is divided by a N-S trending Upper Carboniferous syncline, that shows the same "pinch and swell" structure as the Median Syncline. We are also dealing here with a tightly compressed syncline. Its sediments have developed a schistosity of the same trend as the crystalline schists, thus concealing the angular unconformity normally existing between the Upper Carboniferous and the crystalline rocks. The syncline shows a striking similarity to the carboniferous syncline of the Grand Collet region (chapter III), which is known to be situated along a fault. If this is also the case in the Vizille area, the remarkable difference between fabric and mineral content of the ores east and west of this syncline receives a tectonic background.

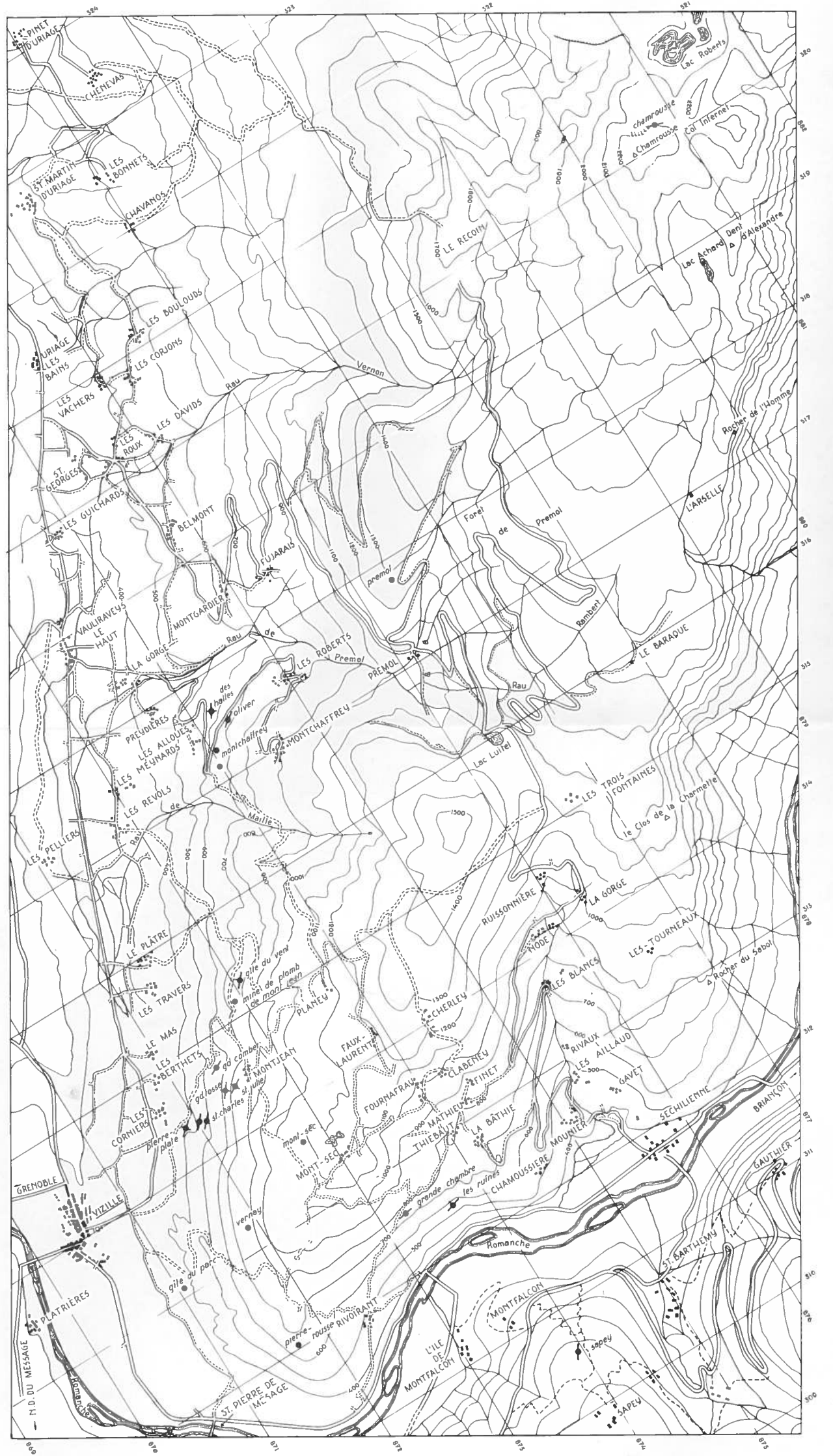
6 Shape and structural features of the ore deposits

All deposits of the Vizille region are vein-type deposits. The veins are true fissure fillings. They have regular walls and their dimensions do not exceed 80 m in either direction. Where well exposed, the walls of the veins are observed to match each other, so that hardly any replacement of wall-rock matter has been involved in the emplacement of the ore body. This feature is remarkable, since the major part of the ore solutions has been of rather high temperature (over 270°).

Veins that show frequent movements taking place along its walls are assumed to be situated on fault-planes or shear joints. Successive phases of movement and subsequent deposition of vein matter have been noticed. The strength and the trend of these movements have influenced the shape and the aspect of the vein. Disruption and entrapment of wall rock are represented by fig. 66 and 67. Strong dislocations resulted in an irregular shape of the vein, the so called "pinch and swell" structure, or in a mechanical contamination of the vein with wall-rock fragments.

Dilatation of the vein walls has enabled the ore solutions to crystallize as large euhedral crystals. In this case little wall-rock matter has been enclosed, unless the filling with ore solutions failed to keep pace with the opening of the fissure. This seems to have happened often in the upper part of the veins. Figure 68 represents the coarse, vugh-like crystallization of Le Vent. There, because of lack of filling material, the walls of the fissure appear to have caved-in in a manner, as might be expected from a fissure reaching the surface.

However, it is known from the quartz inclusions that the fluids involved in the deposition of the vein minerals must have been subject to rather high pressure, hence a deep-seated deposition of the ore is more probable. In the case of the Vizille ores the tendency of the upper part of the vein to cave-



in must be attributed to the proximity of the contact between Triassic and crystalline schists. Fissures arising in the crystalline massif need not have continued up into the Triassic, since the latter's gypsum beds may have failed to transmit tensional forces up into the overlying strata. The youthful morphology allows the reconstruction of the situation of the pre-Triassic peneplain. And indeed, upon reconstruction it appears that the upper part of a deposit like Le Vent must have been rather close to this surface. The strike of the ore bodies shows a remarkable uniformity (fig. 69). This feature, too, stresses the probability that the fissures are moulded upon a joint pattern. Most ore bodies have a steep dip or are nearly vertical. The internal structures of the veins are governed by the successive phases of mineralization.

7 The mineralogy and paragenesis of the ore deposits

For the sake of brevity and ready reference all data concerning the ore deposits have been tabulated (see tables in cover). The significance of the characters and symbols used to denominate the minerals, the type of fabric and their liquid inclusion content is given below.

Pierre Plate
314.4 ; 871.9
alt. 390 m

The numbers under the locality names refer to the E-W resp. N-S position of the veins in the kilometric square system of Lambert, below follows the altitude of the vein.

An arrow or the horizontal sequence of mineral names denote the paragenetical relations.

SIDERITE

The use of capitals point to stress effect shown by the minerals named, such as: cataclasis, undulose extinction, disrupted twin lamellae, the elongated shape of normally isometric minerals, or the intricate, granoblastic fabric as a result of recrystallization.

siderite

The use of normal, lower-case letters means the absence of stress effects.

The size of the characters, whether capitals or normal letters is logarithmically-proportional to the relative quantities of the mineral in question in the vein.

siderite

The length of the dashes designates the grain size of the minerals in true dimensions.



The figure represents the average shape and size of the fluid inclusions (primary or secondary) on 500-fold magnification. From the picture appears the nature of the content at the given temperature (three phases or two phases). The other notations of temperature mark the behaviour of the inclusions on heating or crushing.

20° ↗ 20° ↗ 20° ↗ 20° ↗	The size of the arrow is proportional to the relative amount of gas released on crushing quartz at the given temperature.
30°(3→2)	This notation refers to the homogenization temperature of the CO ₂ -rich phase. If not stated otherwise liquid homogenization is meant.
280°*	The temperature with an asterisk denotes the temperature at which homogenization reaches a maximum.
310°-340°(2→1)	The notation refers to the interval of homogenization of the inclusion's content on heating.

Looking at the table it appears that two types of ore deposits can be discerned. They will be termed type A and B.

Type A is characterized by a flattened fabric of more or less intricately intergrown crystals, showing many signs of stress such as undulose extinction and cataclastic zones. Siderites occurring in this vein type have relatively high manganese and low magnesium contents. Their chemical composition is independent of their geographical situation and occurs in a relatively narrow range in the diagram denoting siderite as solid solution of FeCO₃, MgCO₃ and MnCO₃ (fig. 70). The iron-manganese ratio amounts to about 30.

Sulphide minerals are more frequent and occupy a greater part of the vein than is the case with type B. Their chemistry, too, is totally different. Sphalerite that has not been subjected to recrystallization shows a high FeS-content: la Fayolle, 10.6 mol. % FeS, a figure, that should correspond to a crystallization temperature of about 320° C for FeS-ZnS equilibrium conditions. Other sphalerites are partially or totally recrystallized and display lower FeS-contents, ranging from 4.9 mol. % for a partially recrystallized type of Le Sapey to 2.5 mol. % for the totally recrystallized type of Le Sapey, embedded in quartz (fig. 71).

The dark FeS-rich sphalerite of la Fayolle may contain appreciable quantities of CuFeS₂ in solid solution, as appears from the Cu-content (CuS: 0.95 mol. %). Recrystallization or the intrusion of younger minerals brought about a partial exsolution of chalcopyrite, which may be seen as arbitrarily dispersed CuFeS₂ drops (La Fayolle, fig. 64), or rows of drops concentrated along the contact with younger minerals (Grande Chambre), or individually concentrated masses (Sapey, Les Ruines).

The bismuth content of galena from Sapey also points to a partial recrystallization of this vein, the Bi-content being 0,02 % as against 0,13 % of a non-recrystallized type (Mont Jean). The galena of Mont Jean also has a high silver content (0,13 % Ag).

Ni-minerals such as ullmannite are confined to the A-type deposit. Thus, it may safely be assumed that we are dealing with a mesothermal ore paragenesis at least as far as the non-recrystallized veins are concerned.

Type B is very distinct from type A. Its characteristics, however, are of a negative kind. The fabric is not governed by

ORE DEPOSITS OF THE VIZILLE REGION

1 Pierre Plate 314.4; 871.9 alt. 390m	SIDERITE I Fe/Mn ratio 32 Serrated fusiform Xis intricately intergrown Encloses many wall-rock fragments	siderite II Fe/Mn ratio 35 Of rhombohedral shape. Granoblastic fabric. High Mn-content should be attributed to assimilation of sid. I by sid. II	tetrahedrite bournonite galena chalcocopyrite Veinlets project into sid. II following the cleavages	pyrite QUARTZ I Partly cataclastic Prim. incl.: 21 21* 31 (3-2) 280- 330 (2-1) 300* or: 10 21 (3-2) 270 290 (2-1) 290*	quartz II prim. incl. of the same type as sec. of quartz I, they grade into each other. Prim.: 10 21* 250- 270 (2-1)
2 St. Charles 314.3; 872.1 alt. 480m	SIDERITE I Fe/Mn ratio 33 Altered but identical to siderite I of no. 1, because of equal Mn-content and similar type of fabric.	siderite II Fe/Mn ratio 46 Closely intergrown with, and replaced by ankerite No contamination by sid. I, hence less manganese than sid. II of no. 1.	tetrahedrite chalcocopyrite	pyrite ankerite Fe/Mn ratio 32 Replaces sider. II Pseudomorphous to it Probably results from Ca-metasomatism of siderite II	quartz I Prim. incl. of diff. types: 15 21* 21-31 (3-2) 270-290* 270-330 (2-1) . Prim. incl. grade into sec.: 10 21* 240-270 (2-1)
3 Mine between St. Charles and Grande Fosse 314.5; 872.4 alt. 570m		siderite Fe/Mn ratio 50 Analysis reveals this siderite not to have been contaminated by previously deposed sid.			quartz II Incl. identical to those of quartz I of no. 1 and 2
4 Grande Fosse 314.5; 872.4 alt. 640m		siderite Fe/Mn ratio 49 Large euhedral Xis. no disruption or distorted crystals.			quartz I quartz II Shape and contents of the incl. are identical to those of quartz I of no. 1
5 St. Julie alt. 724		siderite			
6 Grande Combe 314.7; 872.5 alt. 550m		siderite Fe/Mn ratio 67 Fine-grained and cataclastic sid. forms the linings of the vein-walls. The inner part is coarse-grained. This fabric may be due to recrystallization.	tetrahedrite galena	ankerite pyrite Fe/Mn ratio 61 Extremely large cryst. Probably results from Ca-metasomatism of siderite, which also brought on the recrystallization of siderite.	quartz I Two types of prim. incl.: 13 20-31 (3-2) 280* 270-310 (2-1) Sec. prim. of quartz 11: 13 250- 270 (2-1)
7 Mont Jean 315.1; 872.9 alt. 710m	GALENA? SIDERITE I Recrystal. obliterated formerly existing age-relat. Fe/Mn ratio 31 Elongated and intricately intergrown Xis. Fabric and composition are identical to those of sider. I of no 1 and 2	siderite II Coarse crystals of isometric shape	tetrahedrite bournonite galena Bournonite occurs as relics in Ag-bearing galena	ankerite pyrite Fe/Mn ratio 44 Ankerite preferably replaces siderite that has undergone cataclasis, and distortion.	quartz III quartz II calcite Both are vuglinerals. Prim. incl. of water and water-vapour content: 20 180 (2-1)
8 Le Vent 315.3; 873.1 alt. 790m		siderite Fe/Mn ratio 40 Coarse rhombohedral Xis Fabric of the deposit is typical for that of an open fissure vein.			quartz Incl. of seemingly prim. nature are of different shape and content: 20 27-30 (3-2) 250- 295 (2-1)
9 Les Halles 317.6; 874.2 alt. 560m		siderite Fe/Mn ratio 68 Ee/Mn ratio 71 The first ratio refers to a large rhombohedral crystal, the second one to a finely granulated mass. The vein thus, is of homogeneous chemical composition, notwithstanding different types of fabric.	tetrahedrite	pyrite	quartz Displays a series of apparently prim. incl. ranging from large incl.: 20 30(3-2) 300* 295-305 (2-1), to small ones: 10 25 (3-2) 265-280 (2-1) Entrapment of homogen. and heterogen. fluids? Prim. incl. grade into sec. Disruption after sec. phase. no recryst.
10 Oliver 317.5; 874.4 alt. 690m		siderite Fe/Mn ratio 52 Large, euhedral crystals		ankerite pyrite Fe/Mn ratio 52 Ankerite presumably is the result of replacement of siderite by a Ca-bearing solution.	quartz Incl. are of different shape and filling degree. Heterog. entrapment: 20 20* 31(3-2) 240 270-345 (2-1). Homogen. entrapment: 10 25-30 (3-2) 250- 270(2-1) Prim. grade into sec.
11 Montchaffrey 317.3 - 317.8 874.3 - 873.8 alt. 600 - 700m		siderite Fe/Mn ratio 73 Isotropic fabric of equidimensional Xis.			pyrite quartz quartz II Solitary incl.: 20 20* 31(3-2) 295-325 (2-1). Incl. arranged in trains but also prim.: -5 14-31 (3-2) 265-305 (2-1)
12 Le Parc 313.1; 871.1 alt. 390m	SIDERITE Fe/Mn ratio 36 Elongated, fusiform Xis, intricately intergrown.	QUARTZ Incl. reveal zoning: -5 20* 275 (2-1) 310* Note difference between homogeniz. and decrepitation temp.			
13 Vernay 313.3; 871.7 alt. 600m	SIDERITE According to Queyriaud of equal fabric and composition as the sid. of Le Parc	SIDERITE Fe/Mn ratio 31 According to Berthier of equal fabric as Le Parc.			
14 Pierre Rousse 312.1; 871.7 alt. 600m					
15 St. Pierre de Mésage			siderite Fe/Mn ratio 58 Large, rhombohedral Xis.	tetrahedrite bournonite	ankerite pyrite quartz
16 Grande Chambre 312.5; 873.2 alt. 720m	QUARTZ I Its occurrence is restricted to the enclosed wall-rock frags. No prim. inclusions.	SPHALERITE CHALCOPYRITE Fine-grained, black sphal. containing numerous exsolution drops of chalcop. occurring within the enclosed wall-rock frags. refers to the original sphalerite composition. Yellowish-brown sphaler. occurring in the veinswells, within siderite, has been subjected to recrystallization.	GALENA TETRAHEDRITE	SIDERITE Fe/Mn ratio of a fine-gr. siderite occur. in the vein-streaks. 30 Fe/Mn ratio of coarse-gr. siderite occurring in the vein-swells. 30 Equal ratio's point to homogeneity of chemical composition, regardless of fabric.	QUARTZ II No incl. have been preserved in the pinched parts of the vein. Quartz of the vein-swells has retained some prim. incl.: 10 20* 260 (2-1)
17 Le Sapay 310.5; 873.9 alt. 630m	QUARTZ I Quartz cemented a fault-breccia. Strongly granulat. No prim. incl.	SPHALERITE CHALCOPYRITE AND BORNITE The dark, FeS- and chalcop. bearing sphalerite is restricted to chalcop. as an exsolution product (like bornite) and to veins in the wall-rock frags. Sphalerite fragments trapped by quartz II are yellow, and contain little or no FeS, because of compl. recrystalliz.	TETRAHEDRITE ULLMANNITE Occur as veinlets Forms small veins in ZnS and Cpy replacing both.	GALENA Fe/Mn ratio 32 Ratio corrected for Fe- (hydr) oxides contain. the analysis. Siderite impregnates the enclosed wall-rock frags. as scattered small crystals.	QUARTZ II Quartz II altered the shape of the vein from a mineralized shear-zone into a true fissure vein, disrupting previously deposited minerals and wall-rock, and occasioning a recrystall. of embedded minerals. Prim. incl.: 5 20* 250 (2-1)
18 Les Ruines 312.3; 873.7 alt. 450m	SPHALERITE CHALCOPYRITE Sphalerite and chalcocopyrite show intergrowths and mutual exsolution. Sphalerite embedded in quartz has been recrystallized by action of the latter.	TETRAHEDRITE BOURNONITE ULLMANNITE In places bournonite is the product of a replacement of tetrah. by galena.	GALENA Fe/Mn ratio 38 Fusiform Xis, serrately intergrown. Anker. I is the result of a replacement of sider. by calcite (equal Mg-cont. of both ank. and sid.). Fe/Mn ratio ank. I: 28	SIDERITE Fe/Mn ratio 38 Prim. incl. of long, anastomatic shape . 5 22 7	QUARTZ I ankerite II calcite Fe/Mn ratio 21 Low iron content. Mineralization sequence revealed by cockade texture.
20 Peyrere - Langerolle 309.5; 871.9 alt. 980m				ankerite Fe/Mn ratio of ankerite of Langerolle (metasom.) : 60 Peyrere (vein in lime) : 84 On the analogy of Fe/Mn ratio's of the Vizille region, these ankerites are thought to be interaction products of Fe-bearing solutions with Triassic dolomites and limestones, contemporan. with siderite elsewhere.	tetrahedrite boulangerite galena sphalerite quartz Prim. incl. of quartz from the ankerite vein : 20 20* 25-31 (3-2) 285- 305 (2-1)
21 La Fayolle 305; 871.5 alt. 890m	QUARTZ I SPHALERITE CHALCOPYRITE Dark sphaler. speckled at its crystal-boundaries with exsolution-drops of chalcop. has been preserved for recrystall. when embedded in quartz I. Replacement by sider. resulted into a large scale exsolution of chalcop. and loss of iron.	ULLMANNITE Age relations are obscure. Confined to ZnS and chalcop. May have been preserved for recrystall. occurred. Tendency to build euhedral crystals.	GALENA SIDERITE Fe/Mn ratio ankerite : 14 Fe/Mn ratio siderite : 38 Ankerite replaces sider. but in zones of disruption recrystallized siderite projects into ankerite. Although siderite has retained its original composition, the Mn-content is substantially lower than in other similar deposits	ANKERITE	



Fig. 68. Large euhedral crystals of siderite and ankerite (white) from the vug-like deposit of Le Vent, $\frac{1}{2}$ x.

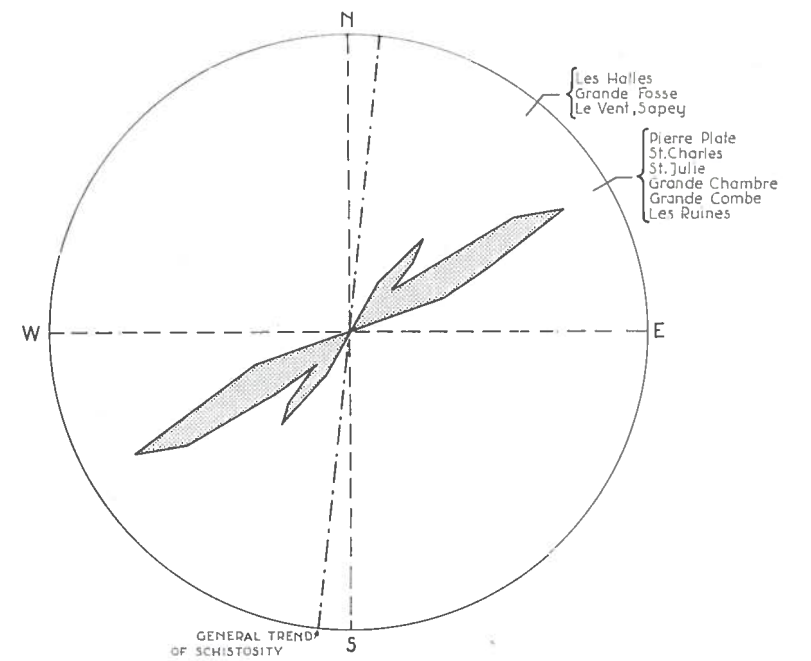


Fig. 69. Diagram of the strikes of the ore veins of the Vizille region, the strike of schistosity varies between N 5° E and N 20° E.

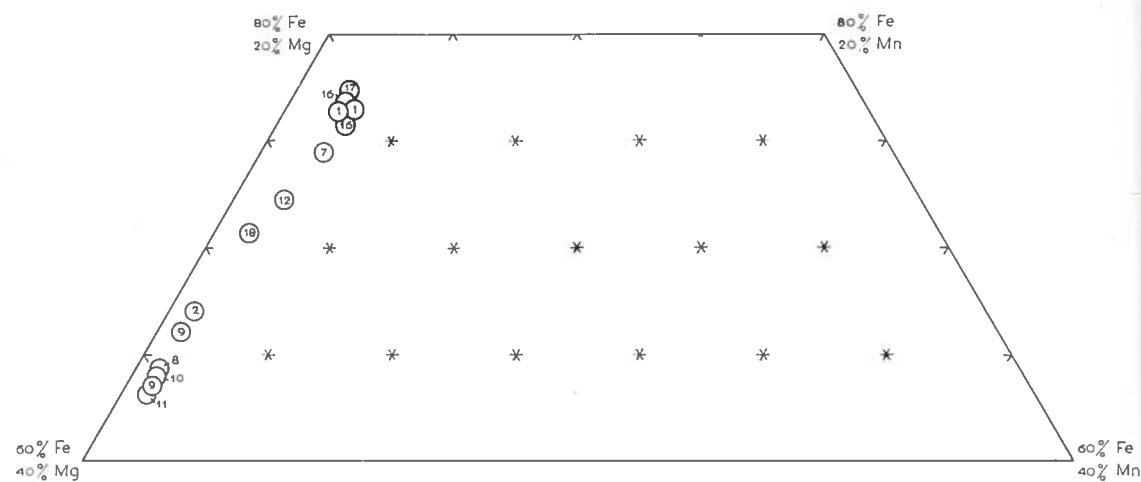


Fig. 70. Composition of the non-altered siderites of the Vizille region.



Fig. 71. Fragments of sphalerite broken down by, and embedded in quartz (light brown to yellow sphalerite). Le Sapay, 1 x.

compression or deformation.

The siderite crystals, for instance, are oriented with their c-axis perpendicular to the vein wall, such as normally occurs with minerals growing in vughs or open fissures. This siderite has low iron and manganese content and a rather narrow compositional range, fig. 70. The iron-manganese ratio has almost doubled with regard to the A-type siderites.

The sulphides are poor in trace elements; sphalerite is almost depleted of FeS (0.5 mol. % for Peyerère and 0.2 mol. % for the deposit of Laffrey).

It is surprising to note that the mineralization sequence is reversed: sulphides followed by siderite in type A, and siderite followed by sulphides in type B. The ore deposits of the B-type are younger in age as shown by the Pierre Plate, St. Charles and Mont Jean deposits, where both types occur. In these deposits the composition of siderite is intermediate between the ideal A- and B-type values, presumably because of contamination.

Their mode of occurrence is also distinct: the A-type prevails in part of the Belledonne's External Zone east of the Carboniferous syncline of Mont Jean and St. Pierre de Mésage whereas the B-type mostly occurs west of this line.

The age of the younger mineralization is known since it can be linked to the mineralization of the La Mure Dôme. The Peyerère and Longerolle deposits, for instance, are of particular interest, as these occur in Triassic limestones, deformed by Alpine orogeny and covering the crystalline basement. Because of metasomatic replacement of limestone ankerite occupies the paragenetic position of siderite of the Vizille area, the sequence being: ankerite-tetrahedrite-boulangerite-galena and sphalerite.

The chemical composition of the Peyerère-ankerite fits into the chemical scheme of the younger ankerites of the Vizille area. South of Peyerère more of these metasomatic deposits occur, they have been described by Sarrot-Reynaud (1957).

The interesting Fayolle deposit also belongs to the La Mure region and occurs in the crystalline basement rocks. The enormous difference between such closely spaced deposits as La Fayolle and Peyerère has, as early as 1912, drawn the attention of Cabrand, (1913) as he remarks that the Peyerère deposits probably result from a rejuvenation of an old vein (Fayolle).

The mineralogical content of both vein types is much alike, and thus, provides no means of distinction between both. It is therefore very difficult, judging from Sarrot-Reynaud's description, to decide to which type the ore deposits protruding up into the Carboniferous belong.

Neither strike nor dip of the veins, as shown by the diagram (fig. 69), does provide any information about mutual age relations, since A- and B-types are equally distributed over the orientation maxima. This will also be shown to apply to the Allevard region with much more data. There the vein trends are to be regarded as feather joints of a wrench fault system, an idea that may also hold for the Vizille region, if the trend of the schistosity bears any relation to that of the wrench faults, since the maxima of Vizille differ for the same number of degrees as does the schistosity, both being rotated about 15° to the north.

Another indication for the idea that Peyerère and in a general

way all La Mure deposits occurring in the Mesozoic sediments belong to the same mineralization phase as the younger ore suite of Vizille, comes from the investigation of the quartz inclusions. The younger vein quartz of Vizille contains the same kind of inclusions as are observed in quartz veins of the Laffrey, Longerolle and La Mure deposits, equally displaying a high CO₂-content (about 10 mol. %) and high homogenization temperatures (mean value of 300°). The dependence on level of deposition, controlling the density of the CO₂-rich phase, is not so obvious as in the Allevard region, although some outcrops of ore deposits come very close to the Triassic peneplain. In the Vizille region only the high-level Mont Jean and Oliver deposits have a close to the critical density of the CO₂-rich phase, the latter homogenizing into a liquid phase by the sudden disappearance of the liquid-vapour boundary. The lower situated veins display an expanding liquid CO₂ phase and thus have higher CO₂ densities. The slighter susceptibility to level of deposition differences, as compared with the Allevard region, has to be attributed to a thicker cover of Mesozoic sediments.

Actually, the stratigraphical series are more complete and thicker in the La Mure region.

The fluid inclusions, the chemistry of the paragenesis and the geological situation thus have made sure an Alpine age for the younger undeformed mineralization suite of Vizille.

The mineral content and chemistry of the younger paragenesis might suggest an epithermal ore type, an environment which seems not to agree with the high homogenization temperatures of quartz. The mesothermal type on the other hand is accompanied by quartz of low homogenization temperatures (260° - 270°). These temperatures, if taken for crystallization temperatures, also seem incompatible with the ore type. The very narrow range of homogenization temperatures, however, has been explained as a result of crystallization from a homogeneous medium, which means the necessity of applying a pressure correction, possibly increasing the actual crystallization temperature considerably.

If both types belong to the same mineralization cycle, there should exist a certain zonal arrangement between them, which is absolutely lacking. Not even a gradual transition or intermediate stage is found between their mineral contents, nor are they separated in space, since both types may be present in the same deposit (Pierre Plate, St. Charles, Mont Jean and Les Ruines).

Further more an effort to attribute both mineralizations merely to one metallogeny occurring in two phases, is rendered improbable by the common presence of stress effects in the mesothermal suite and the absence of it in the younger suite as well as by the incongruence between the homogenization temperatures of both quartz phases, the older needing to be corrected for pressure, whereas the younger homogenization pressure equals the crystallization pressure.

The idea that the younger mineralization represents an Alpine rejuvenation of an old (possibly Hercynian) deposit agrees exceedingly well with the data, since it explains:

- the isotopic composition of galena (part II)
- the identical mineralogy of an impoverished chemistry
- the reversed mineralization sequence
- the high temperatures of the regenerating solvents that are supposed to be necessary for accomplishing a re-resolution of

- the whole vein content
- equal strike and dip of both vein types
- their close association in space
- the abrupt transition (the ore having been rejuvenated or not)

In certain tectonically defined areas the old mineral content has been better preserved in its original state, only being recrystallized upon tectonic dislocations, than in others. The eastern part of the Outer Zone represents such a tectonic block. Such a tectonic entity will be dealt with more closely in the Aiguebelle chapter, the ore there being exclusively located in the eastern part of the Outer Zone.

8 References

The fact that most veins, poor ones included, have been mined and decreed in the eighteenth and nineteenth century was of great value for locating the ore bodies. This is supported by the fact that in an area well-known to the author as that of Allevard only a few veins were found that had not been mined and recorded. The informations obtained from the local population generally turned out to be of little value, since most inhabitants appear to be unaware of the mineral resources of their country. The main reason for it probably is the considerable time that has elapsed since the mines have been closed down. The greater part of the descriptions and mine reports are as old as the mining activities themselves.

The earliest publication consulted by the present author is Guettard's "Minéralogie du Dauphiné" (1779), a geological itinerary in an area covering the present Isère Department and some districts south of it, the so called Dauphiné region. Guettard describes the Pierre Rousse mine and a mine near St. Barthlémy. The latter matches the Sapey deposit in mineral content. Lacroix has edited in 1919 a manuscript of Dolomieu (1795) on the iron ore deposits near Vizille. Dolomieu does not mention names of mines, but gives a description of deposits that fits very well the characteristics of the Pierre Plate, St. Charles, Les Halles, and Le Parc mines.

The present author owes the greater part of his information about the situation of the ore deposits to E. Gueymard (1844). In volume I of his study, sponsored by the Statistical Society of the Isère Department, Gueymard gives a comprehensive geographical, geological and mineralogical description of the Department. The Oliver, Grande Chambre, Le Sapey, and Mont Sec deposits excluded, all mines have been recorded by him. His study includes a historical outline of production and mining methods, some dip and strike measurements, and analyses of siderites. The latter are generally of poor quality.

The handbooks of Lacroix on the Mineralogy of France (1893), and Hintze's "Mineralogie" (1904) summarise much of what has previously been published on this area. Chabrand's "Geographie Minière des Alpes Dauphinoises" (1913) contains the most recent reference to a large number of abandoned mines in the Vizille area.

Studies of more limited scope were carried out by Collet-Descotils (1806) presenting analyses of the siderites of Pierre

Plate and Les Halles, by Hericart de Thury (1807) on the silver content of a galena-bournonite ore of Mont Jean, by Berthier (1828) analysing the siderites of Pierre Rousse and Grande Fosse and the ankerites of Corniglion (probably Grande Combe according to data of Gueymard) and Le Vent. Doelter (1911) records the analyses of Berthier, Ch. Lory (1865), Rath (1817), Groth (1885) and Lacroix (1893). Sarrot Reynauld (1957) adds new data to the mineralogy of the deposits of St. Pierre de Mésage.

Historical and geographical reviews of the region have been written by Allix (1917) who deals with Grande Chambre and les Ruines, by Molmerret and Bruant (1936) who describe Le Vent, Les Halles and Oliver, and by Blanchard (1941) who gives the most up to date geographical information.

The maps of the "Archives des Mines" in Grenoble were of great help in locating the Pierre Rousse, Grande Chambre, Les Ruines, Le Sapey and Mont Sec deposits.

CHAPTER II THE ORE DEPOSITS OF THE ALLEMONT REGION

1 Geographical setting and morphology

Among the ore districts of the Belledonne the Allemont region occupies a special place mainly because its deposits occur in the Inner Zone, a part of the Belledonne that is generally devoid of ore mineralization. Actually, the ore deposits only occur in those parts of the Inner Zone where large outcrops of granite are absent and the position of the pre-Triassic penneplain can be traced by erosion relics of the sedimentary cover.

Obviously, such an area is not as easy to define geographically nor geologically as are the Vizille and Alleverd regions.

The Allemont region comprises the part of the Belledonne Massif dominated by the pinnacle-like summits as the "Trois Pics de Belledonne" (2970 m) and the northern part of the Taillefer Massif, which is the continuation of the Belledonne Massif south of the river Romanche.

The Median Syncline forms the western border of the region. Its position is marked by a sudden change in relief; east of it the mountainous relief of the crystalline rocks, west of it the intermediate land-scape forms of the Liassic sediments ("Collines Liasiques" and Grande Serre).

To the north the region ends in a wedge shape between the Median Syncline and the granite massif of Sept-Laux. The N-S trending Pleynet and Eau d'Olle rivers run parallel to the fault contact between the Allemont Massif and the granite of the Sept-Laux Massif.

Much of what has been said about the morphology of the Vizille region also holds for the area being discussed now, the main feature being the youthful morphology. Upper Carboniferous strata are still present on the summits of the mountains, notwithstanding the fact that the greater part of the sedimentary cover has slid away.

The drainage system is only of a primitive nature, especially on the eastern side of the Belledonne Massif. Numerous small parallel torrents run straight into the deep, but narrow valleys of the river Romanche and the lower reaches of the Eau d'Olle river.

On the western side of the Belledonne, where the presence of the "Collines Liasiques", or a well developed Outer Zone, has increased the distance between the central crest and the base level of erosion, a more complex system of streams and torrents has developed, the streams showing a greater tendency to branche.

The valley of the river Romanche owes its deep excavation both to a subsidence of the base level of erosion, and to an epeirogenic uplift of the Belledonne Massif. Although minor

streams are known to follow faults, joints and other dislocations the great valleys of the Romanche, Arc and Isère are not necessarily based on such dislocations. The deep and narrow character of these valleys may also be explained by assuming that consequent rivers, flowing down from the higher, interior parts of the Alps, into the "Combe de Savoie" and the "Grésivaudan", have cut deeply into their beds by a later epirogenic uplift of the Belledonne Massif as a whole. Such an epigenetic nature is clearly demonstrated by the small Massif of le Châtelard. There the river Arc has not been diverted by the hard rocks of the crystalline massif, notwithstanding the fact that this Massif is bordered by friable shales of the Lias. The sole explanation for this phenomenon is an uplift of the Châtelard Massif, which has kept the river in its original bedding.

2 Historical notes on the ore deposits

Mining has played a prominent part in the economical development of the Belledonne Massif, since the exploitation of the ore deposits is known to be very old, the silver mines of Chalanches and Oulles excepted.

Many villages such as Articol, Allemont, Livet, Gavet and Rioupéroux owe their origin to mining and related activities. Apart from the ore deposits, the region is endowed with rich natural resources such as water-power of the rivers Romanche and Eau d'Olle, constituting a source of power for the water-driven hammers, the so-called "martinets", and extensive forests for the production of charcoal for the furnaces.

The existence of mining activities in the fourteenth century is known from a decree ordering the cessation of mining in order to prevent disastrous soil erosion due to deforestation. The roasting of siderite consumed enormous quantities of timber. At several epochs such a decree has been enacted. Notwithstanding their high calcium content, ankerite being very common, the Allemont siderites drew a much earlier attention than the Vizille ores. This is explained by their low magnesium content, magnesium tending to raise the fusion point of siderite, by the advanced stage of alteration shown by most siderites, facilitating the smelting process, by the magnetite content, upgrading the ore, and by the high ($\pm 10\%$) manganese content of the steel produced.

In the early part of the eighteenth century most mines are recorded to have been abandoned. But the discovery of the rich silver ores of Chalanches in 1767 gave the region a new lease of life. Allemont became the most important town of the Belledonne Massif, owing to the construction of large furnaces for roasting, smelting, and refining of silver, and cobalt ores, as well as the gold ores from the adjacent Gardette mines. Many small veins were taken in exploitation again because of the hope to strike some other silver veins. Like in the Vizille region, all mining activities ceased about 1865. At that time they were the property of the "Société des Hauts Fourneaux de Rioupéroux", which decided in 1865 to make no further use of the local minerals.

3 Mining methods and exploitation data

The early attention that was paid to the siderite veins of the Belledonne area has been mentioned in section 2. Particularly well known were the deposits of Grande Bois, being the richest, and Lac Crop, being the most elevated (2400 m) and producing the best grade of ore. The ore of the Les Essarts deposits has been recorded in the fourteenth century as being of a very poor grade, "producing more scoria than metal", which is not astonishing in view of the nature of the ore, being ankerite (Sclafert 1926^a).

At the time of the visit to the region by Guettard in 1775 most siderite veins were abandoned, having been mined out completely except Grande Bois, which was closed in 1836. About that time Gueymard, the "Chef des Mines" of the Isère Department, investigated all deposits of the area in the hope of finding a new deposit of Grande Bois size, but his efforts turned out to be vain. St. Charles and Roche Noire were examined in the outcrops, and Trois Laux and Malpourchié were explored by new drift tunnels. These drifts are among the few works other than surface excavations practised in the mining of siderite.

The mining works of the small Cu-Pb deposits of Roche Moutas, Chamrousse and Vaudaine, too, are just superficial trenches. From the data of Guettard (1779) no conclusions can be drawn about the age of their active period.

Much more is known about the Chalanches and Oulles deposits. Chalanches was discovered in 1767, exploited during one year by the inhabitants of the region, and seized by the Government in 1768, who charged Mr. Schreiber with the geological investigation and management of the mines and the construction of blast-furnaces for the smelting of the ores. The benefits of the silver production (7000 kg) were granted to the brother of King Louis XVI till 1792, in which year the mines were nationalized. After having been operated for a short period by the revolutionary government, the mines were leased to a private company due to lack of profit. This company exploited Chalanches until 1811, the mines then being believed to be depleted of silver. In 1843 the Company Surell obtained the exploitation rights for cobalt. Chalanches was definitely closed in 1867.

Afterwards many mineralogists, prospectors and tourists have visited the abandoned mining works, Chalanches being the most famous silver mine of France, and have given themselves much efforts to bring home some ore specimen. Thus, even Groth visiting Chalanches only 18 years after its closure was not able to find anything of mineralogical value in the waste piles outside the tunnels. The present author, too, had to be content with some 30 rather poor specimen collected by himself, 10 specimens of the rare Chalanches minerals from the National Museum of Geology and Mineralogy at Leyden, and 5 specimens from Teylers Museum in Haarlem.

The mining of the deposits was performed by a rather complicated system of drifts, cross-cuts, raises and winzes following the stock-work of the veins. All works are confined to an area of 600 x 500 x 300 m. There was no question of systematic mining methods, the grade of the ore, the trend of the veins, and the shape of the small ore shoots appeared to be too haphazard (fig. 72).

The area of the Oulles deposit, showing lead mines of presumably very old age, was investigated and promoted to production by Gueymard in the early part of the nineteenth century, but is was closed soon afterwards because of the long distance to the Allemont furnaces. Its ore was smelted in Allemont for the silver content of the galena. The small deposits of La Fare and Roche Moutas have only been worked on a tentative basis.

4 Geological outlines

The country rock of the Allemont ores belong to the formations of the Inner Zone. The Inner Zone rocks have a complicated history, which, in a general way, is marked by seven events. An attempt will be made to deal with them in a chronological order. A section is represented by fig. 73.

a. Basic and ultra-basic rocks

A folding phase older than or simultaneous with an intrusion of basic rocks produced large isoclinal and fan-shaped folds.

The basic intruded masses are concordant and conformable with the adjacent rocks. The main intrusive body can be followed from Le Tabor (in the southern part of the Taillefer Massif) over a distance of 35 km to the Pics of Le Ferrouillet and the Pas de la Coche (in the northern part of the Allemont region).

The central part of this basic intrusive body consists of diallage-peridotites and olivine-gabbros, the mineralogical composition of which has been changed by later serpentinization and uralitization. A comprehensive description of the serpentinites of Le Tabor is given by Choubert (1934), while den Tex (1950) has made a detailed study of the ultra-basic and basic rocks of the Lac Roberts area.

The peridotites are bordered by a zone of rocks of gabbrodioritic and dioritic composition. The width of this zone varies from some hundreds of metres to 2-3 kilometres. The volume of the basic intrusives of this type is much greater than that of the peridotites and serpentinites. Among the chief minerals of the gabbro-dioritic complex, plagioclase (40-70% An) and diallage, obviously belong to the original igneous assemblage. A mineralogical and structural change has altered part of these gabbro-dioritic rocks into amphibolites, a rock-type that forms a prominent constituent of the crystalline rocks of the Belledonne Range, as compared to other Hercynian external massifs of the Alps.

The amphibolites that show evidence to have been derived from gabbro-dioritic intrusive rocks are designated by Tobi (1959) as the Ferrouillet amphibolites. The Ferrouillet is the northernmost summit of the central crest of the Allemont region. Generally, the amphibolites form pinnacle-like summits. The age relation between the basic and the ultra-basic rocks is difficult to establish, since the contact between both types is a tectonized one, and later phases of metamorphism have changed the original mineral assemblage. From the Q-L-M diagram and the K-Mg diagram (P. Niggli and C. Burri, 1945), den Tex (1950) concluded that the sources of both intrusive rock-types must be related.

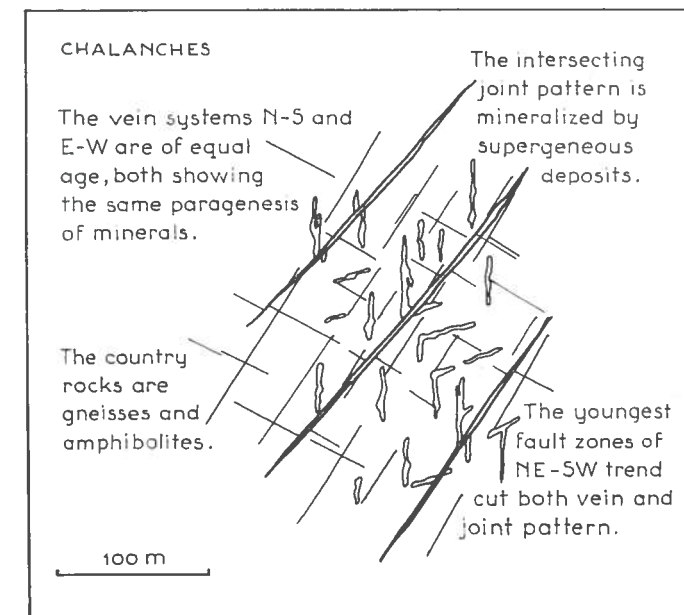
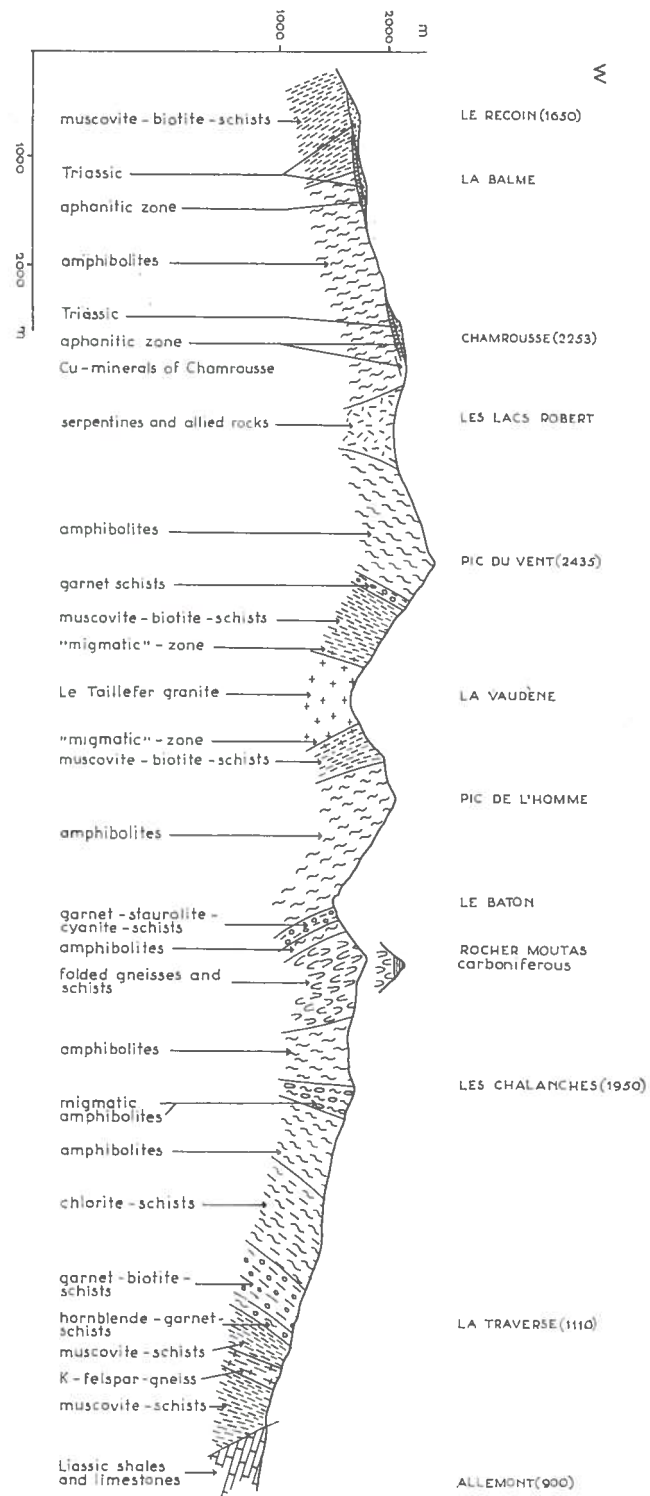


Fig. 72. Idealized representation of the mineralized joints and fault-breccias of Chalanches according to data of Hericart de Thury (1806), Gueymard (1844) and personal interpretation.

Fig. 73. Cross-section of the Allémont region, according to data of Den Tex (1950), Maron (1955), Michel (1958) and personal observations. The term "migmatic zone" of the Taillefer granite is of Michel, and denotes a schistose border zone of the granite.



b. The main phase of metamorphism

Mesozonal metamorphism has affected the greater part of the Inner Zone's igneous and sedimentary rocks. According to their composition, the meta-sediments of arenaceous and argillaceous origin have been transformed into: garnet-stauroilite-cyanite-schists; garnet-biotite-schists, garnet-muscovite-schists; and muscovite-biotite-schists. This metamorphic series mixed with some amphibolitic material, occurring near Lac Crop, is designated by Tobi (1959) as the Lac Crop formation.

The meta-sediments of graywacke facies and detrital basic igneous rocks (Kalsbeek 1962) have been transformed into: banded amphibolites, epidote-amphibolites, and plagioclase-amphibolites. The plagioclase of these rocks may contain as much as 40% An. Hence, it may be difficult to discriminate between para- and ortho-amphibolites. The prevalence of certain twinning laws among the plagioclase, the presence of pyroxene relics, plagioclase of labradorite composition, the shape and quantity of zircon and the abundance of titanite may be tools for distinguishing between both kinds of amphibolite (Tobi, 1959, Kalsbeek, 1962).

The age of the mesozonal metamorphic phase is not easy to fix in the complex metamorphic history of the Belledonne, because of the effects of later phases of retrograde metamorphism.

Tobi (1959) and Kalsbeek (1962) share the opinion of Choubert (1934) and assume, the main metamorphic phase to be younger than the emplacement of the basic rocks, for reason among which is the uniform grade of metamorphism attained by well ortho-amphibolites as well as meta-amphibolites and acid gneisses.

c. Emplacement of the granites

Though according to Bellair (1948) the granites of the Inner Zone of the Belledonne are not necessarily of the same age, they nevertheless are grouped together here before dealing with the Upper Carboniferous deposits, since most of them are known to be at least pre-Triassic (Taillefer) and a pre-Westphalian D age could be ascertained for one granite (Outray).

Many outcrops of granite are found in the Inner Zone of the Belledonne, most of them represent individual intrusive bodies. From north to south there are:

- the granites of Chaudanne, Outray, Beaufort and Bersend in the Beaufortin district;
- the granite of the Grande Lauzière and St. Colombar;
- the granite of Epierre, Grand Charnier, and Sept-Laux;
- the granite of Le Taillefer and Livet;
- the granite of Entraigues.

The elongated shape of the outcrops suggests that the form of the granite has been controlled by tectonic dislocations. Indeed, tunnels traversing the granites of Epierre and the Grande Lauzière have revealed a tabular shape of the granite bodies parallel to the general trend of schistosity of the adjacent schists. In places however, the proper dimensions of the granite body may be difficult to establish, since there appears to exist a gradual transition between the apparently isotropic fabric of the central part of the granite body and the schistose border zone, the so-called "granite-protogine". The

fabric and the mineral composition of the border zone, especially of the Grande Lauzière, are such that a hand specimen is hardly distinguishable from the epizonal schists of the Inner Zone. If the intrusive character of the granites had not been demonstrated by E. Niggli (1953), one would be inclined to suppose a metasomatic origin. The investigations however, of Tobi (1959) have revealed this alteration of the granite to be due to an intensive mylonitization under epizonal conditions. The subjected parts have become muscovite-sericite schists with rather large feldspars that appear to have survived the mylonitization. These rocks have been named "schistes feldspathisés" by Bungle (1931), and are described by Bordet (1957) as "Migmatites of the Serie Verte". The granite of Livet should have a similar "migmatic" zone, according to the description of Michel and Berthet (1958).

Not all granite bodies have broad outer zones of "schistes feldspathisés" sometimes, a fault zone forms its boundary. When establishing the relation between the position of the granites and the ore deposits one has to keep in mind that the spatial relation-ship may have been greatly affected by fault displacements. One of these belongs to a fault system that was active during the later stages of consolidation of the granite and that caused the elongate, lenticular shape of the granites in particular and stretching of the Belledonne as a whole.

If one regards the granites as the ultimate source of the ore deposits this fault system may have effected a horizontal displacement of either formation, whereas a rejuvenation of the faults, causing a relative uplift of the intrusive bodies have occasioned a vertical displacement. Such a fault system of the second type occurred during the Alpine orogeny.

d. Upper Carboniferous

Sediments of Westphalian D and Stephanian A are the oldest rocks that can be dated. Their angular unconformity with the formerly mentioned formations is apparent.

An unconformity between granite and Upper Carboniferous has been observed in the Beaufortin district (the Outray granite) but other events such as the emplacement of the basic complex, the main phase of mesozonal metamorphism, and at least one orogenic phase, will also have taken place before the deposition of the Upper Carboniferous.

The Upper Carboniferous mainly consists of black shales and intercalated coal seams, Tobi (1958) has noted that a great deal of the sediments is of tuffaceous and rhyolitic nature. In relation to this feature it is appropriate to mention here the rhyolites forming part of the Upper Carboniferous of the Grandes Rousses Massif. The latter Massif is situated east of the Belledonne.

The Upper Carboniferous of the area investigated occurs in two tectonic positions. One type is pinched into deep synclines (viz: Median Syncline and bordering synclines) whereas the other type is found to constitute flat horizontal coverings on the summits south of the EW-fault that crosses the Pas de la Coche. The latter type has drawn the attention of many geologists, for it represents the first unconformity to have been observed between the crystalline rocks and Palaeozoic sediments in the



Fig. 74. View from the east to the central ridge of the Allemont region. The position of some siderite deposits and the almost horizontal Upper Carboniferous covers are indicated.

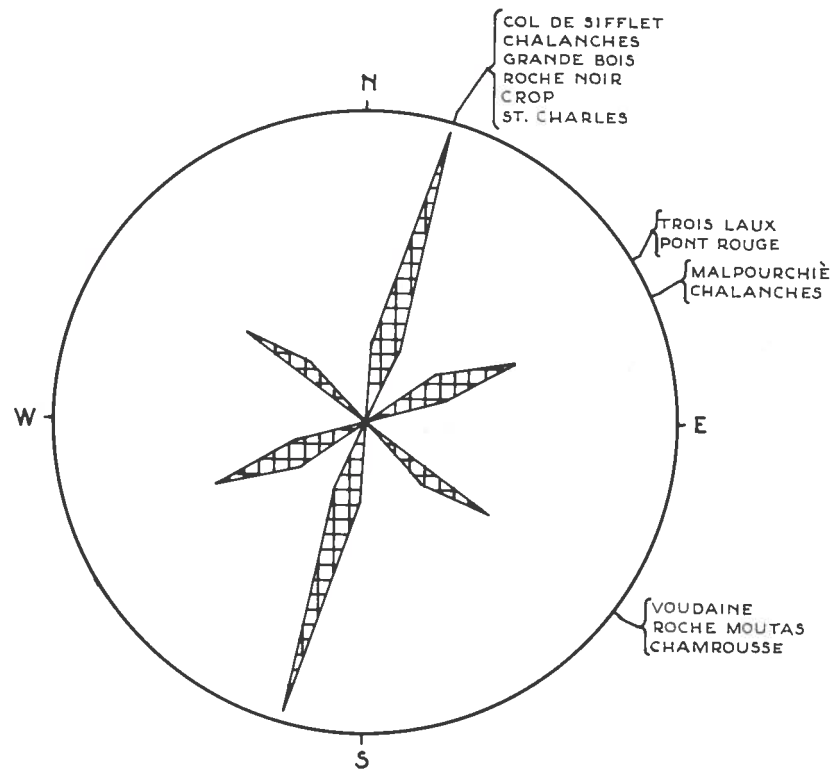


Fig. 75. Strike diagram of the ore veins of the Allemont region.

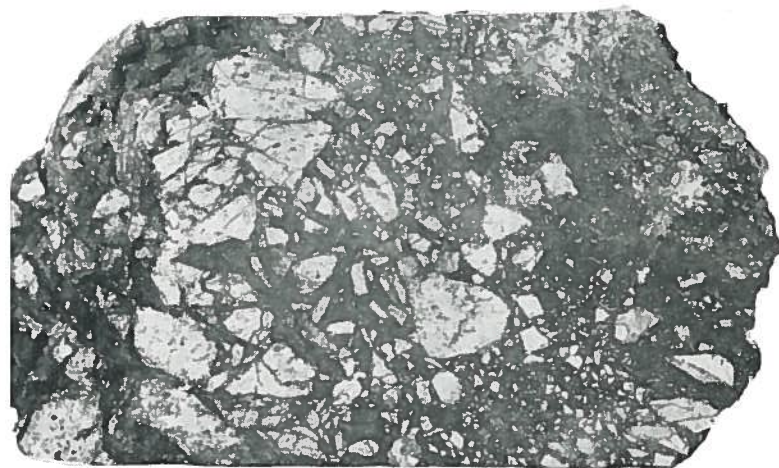


Fig. 77. Fault-breccia mineralized by ankerite of Grande Bois composition. Pont Rouge-Ruisson, 1 x.

External Massifs of the Alps (fig. 74).

The Carboniferous of the Median Syncline has much greater extension than the horizontal coverings have.

Some coal-seams (those of la Boutière and St. Mary) have been exploited. They may be correlated with coal beds in the La Mure district.

e. Hercynian orogeny

One phase of the Hercynian orogeny can be dated by means of the feature that sub-horizontal Permian sediments of the Allevard region are unconformably overlying a wedge of Stephanian A sediments, deeply folded into the crystalline basement. This unconformity probably represents one of the latest phases of the Hercynian orogeny.

The next older phase that is recognizable is the development of the wrench-fault system, contemporaneous with the granite emplacement, which generally is considered to be also of Hercynian age. This phase may have accomplished a retrograde metamorphism of green schist facies (Kalsbeek 1962). Mylonitization, cataclasis and replacement of mesozonal minerals by chlorite, sericite, and albite have thoroughly changed the former nature of the crystalline rocks. The features are most conspicuous in the Inner Zone, where the original degree of metamorphism was higher.

In consequence of the chloritization of iron-rich minerals of originally different types of schists, such as biotite-schists, garnet-schists, amphibolites and garnet-staurolite-schists these rocks have become very similar in composition, viz: quartz-chlorite-sericite-schists.

From the chemical analyses of the chlorites in the region under discussion it may be concluded that the retrograde metamorphism of amphibolite has not given rise to solutions rich in iron, a feature that Angel (1939) regards as a phenomenon accompanying retrogressive metamorphism.

A great deal of andesine or oligoclase has been transformed into albite. Epidotisation of amphibole rocks is frequent.

Tobi (1959) has noted the remarkable resistance of albite and potassium feldspar to mechanical stresses. The albite porphyroblasts of the Outer Zone seem hardly to have suffered from the dynamo-metamorphism. The comparatively fresh feldspar in the fine grained masses of sericite and quartz in the Outer zones of the granite bodies are so conspicuous as to suggest feldspatization (Bunge, 1931, Bordet, 1957). Actually, they represent the feldspar of the mylonitized granite.

The retrogressive metamorphism has not affected all crystalline rocks of the Inner Zone to the same extent. Some tectonically defined areas have suffered strongly, whereas others appears to have been almost exempt from it. The triangular area confined by the Median Syncline, the fault bordering the western side of the Sept-Laux Granite Massif and the ENE-WSW wrench fault of the Pas de la Coche provides a good example of such a highly cataclastic area; north of the wrench fault sericite-chlorite-schists prevail, whereas south of this fault chiefly unaltered amphibolites and mesozonal schists occur. Although folding seems not to have been important during this Hercynian orogenic phase, further crustal shortening of the rigid

crystalline masses may have been achieved. Bellière (1958), describes how numerous minute slip movements along schistosity planes result in a conspicuous change in the dimensions of the affected schists.

f. Mesozoic sediments

Grès d'Alleverd

Plant imprints (Corsin 1954, Tobi 1959) have proven the arenaceous sediments, known under the name Grès d'Alleverd that unconformably overly crystalline rocks and folded Upper Carboniferous to be of Permian age. In the area under discussion they chiefly occur in the Median Syncline, attached on its hanging wall. The Syncline dips to the east at an angle of about 30° - 60° . Only on close scrutiny (Jansen, 1956) it is visible that the Grès d'Alleverd is overturned. The pronounced cleavage, cutting the bedding planes at high angles, may be deceptive in this context. The Grès d'Alleverd will be described in greater detail when we come to deal with the region of Alleverd, where it is common as country rock of the ores.

g. Triassic

Triassic formations are very well displayed at Chamrousse and Le Recoin. The unconformity between the crystalline rocks and the almost horizontal covering of Triassic sediments is conspicuous.

The Triassic comprises:

- Limestones
- Cavernous Limestones ("Cargneules")
- Spilites
- Sandstones

The crystalline rocks bordering the overlying Triassic sandstones shown an intensive alteration, such as is believed to result from weathering conditions. They have been called "aphanites" by Ch. Lory (1861). This zone of alteration bears a close relation to the stratification of the Triassic, and hence, is thought by den Tex (1950) and Michel (1961) to originate from Triassic supergeneous alteration. Thus, both "aphanites" and Triassic deposits may indicate the position of the pre-Triassic peneplain.

Many Triassic coverings are found on the crests and summits of the Taillefer Massif. These are situated at different levels, and thus suggest, that the faults along which horizontal displacement took place earlier, have been rejuvenated by vertical movements of post-Triassic age (Sarrot-Reynauld, 1961). Sediments of Triassic age, occur also in the Median Syncline, these are intricately folded.

The importance of the Triassic in relation to the gliding tectonics such as displayed in the Alleverd region justifies a closer investigation of its sediments in chapter III.

h. Lias

A fault marks the contact between the crystalline rocks and the Liassic shales on the eastern border of the Allemont region.

i. Alpine orogeny

The main effects of the Alpine orogeny in the Inner Zone are faults. Many Alpine faults have used Hercynian discontinuities, and are only recognizable as Alpine phenomena, when they have affected Mesozoic sediments. The similar behaviour of the crystalline rocks during the later phase of Hercynian orogeny and the Alpine orogenetic phases has rendered it difficult to distinguish between the specific results of either orogeny. There is, for instance, no yardstick yet by which to measure, during with orogeny retrograde metamorphism has been most effective.

Generally, (Bellair 1948; den Tex 1950; Michel 1958; Tobi 1959; Kalsbeek 1962) the Hercynian retrogressive metamorphism is believed to be the more important one. The Alpine orogeny is characterised by thrust-faults and normal faults mainly.

5 Structural geology

The ore deposits are not so closely spaced as to show a definite relationship to the tectonic dislocations. However, it may be concluded that there is an indirect relation, since the ore deposits display a control of their location by the position of the pre-Triassic peneplain, a position which in its turn, is governed by faults. The position of the peneplain is given by erosion relics of the Triassic cover (such as the Chamrousse, 2250 m, and the Recoign exposures) or by the "aphanatic" alteration zone. The sub-horizontal Upper Carboniferous caps on certain summits of the Allemont region (Roche Moutas, 2646 m; Grande Lauzière, 2740 m; Grande Lance de Domène, 2790; Les Roches Rouges, 2800 m; Rocher Rousse, 2750 m and Roche Noire, 2700 m) may also help in locating the pre-Triassic peneplain, since the Permian is known to be absent, and Upper Carboniferous has only possessed slight thickness. It may be convenient to review the faults controlling the position of the peneplain, although some of these faults have already been described in the former section.

a. The Median Syncline

A major feature of interest is the Median Syncline. Its complex nature has been disentangled by P. Lory (1925) and Tobi (1959). From their studies and cross-sections it appears that the Median Syncline does not represent a syncline in the true sense of the word, but has to be regarded more properly as a fault along which Upper-Carboniferous and Mesozoic sediments have been entrapped into the basement during the Alpine orogeny. The plasticity of the Triassic gypsum-beds have enabled the thrusting movements to cause an intricate folding of the Median Syncline's content. By this process the Upper Carboniferous sediments belonging to the cover of the Outer Zone and to the bordering Hercynian synclines have also been drawn into folding and have become intermingled with the Mesozoic rocks in such an intimate manner as to make it hardly discernable which part of the Median Syncline owes its structure to the Alpine orogeny and which to the Hercynian orogeny.

b. Faults bordering the basic and ultra-basic rocks

The ortho-amphibolite bodies and ultra basic intrusive rocks are mainly bordered by faults (den Tex, 1950).

c. Wrench fault system

A wrench fault system of conjugate ENE-WSW and NNW-SSE trending faults has affected the formations of Inner Zone provoking a lenticular shape of the granite outcrops.

There are reasons, such as the nature of the mica fabric, to assume that the faults are penecontemporaneous with the intrusion of the granite (Kalsbeek, Koning and den Tex, 1961). This may explain why the faults die out in a westerly direction in the granite, and do not reappear at its western border in the extrapolated position. Some of them are thought to continue along the granite-host rock contact. Later rejuvenation of these faults resulted in a upthrust of the granite.

The ENE-WSW trending fault crossing the Pas de la Coche belongs to the same system. It separates a triangular northern block, which has suffered highly from mylonitization and retrograde metamorphism, from a southern block that shows less signs of retrogressive metamorphism. The particularly strong mylonitization of the northern block should have been caused by its tectonic position, this area being pinched between the thrusting masses of the Sept-Laux granite on its eastern side and the resistant Outer Zone on its western side. Owing to the Hercynian and Alpine orogenies, this southern part has gained a more elevated position, and subsequently has escaped the compressed deeper zones of the Belledonne. The fact that exactly this part of the Inner Zone has been overthrust on the Outer Zone explains the rarity of broad mylonitic zones in this southern block.

d. The faults of the Lac de la Jasse

Inside the highly altered triangular northern block of the Inner Zone a wedge-shaped outcrop of schists of the Outer Zone and adherent Carboniferous occurs. The margins of this wedge constitute faults. These faults are parallel with and close to the Median Syncline. There is a little information available about the age of these faults, whether Hercynian or Alpine.

6 The structural features of the ore deposits

Most ore bodies are fissure veins, and are situated on joints or faults (fig. 75). All these mineralized dislocations are of minor importance as faults. Some are about parallel to the schistosity. One can state that, as a rule, the major faults in the Belledonne never have been mineralized to any great extent. The differentiated nature of the wall rock makes the observation of displacement easier than in the rather uniform schists of the Outer Zone. The fault character of the fissure veins may also be apparent from the presence of slickensides on the vein walls, the rather uniform strikes of the veins, and the fact that many brecciated country rock fragments have been enclosed.

Generally the veins are smaller, narrower and have less continuity than the veins of the Vizille area. The actual size of the ore shoot is difficult to delimit, even within a single vein due to the arbitrary replacement of the ore by ankerite and calcite.

A second reason why difficulties are met in estimating the ore reserves, is the feature that much ore is present as a secondary enrichment in joints and fissures adjacent to the veins.

Supergeneous alteration phenomena appear to be important in the ores of the Allemont area. The siderite veins are coated with thick crusts of goethite and lepidocrocite, and the richest parts of the Chalanches silver ores are found in fissures containing a powdery form of native silver besides all kinds of supergeneous minerals such as asbolan, goethite, erythrite, annabergite and gypsum. These alteration products are of frequent occurrence in the joints intersecting the veins.

Among the general characteristics of the ores of the Allemont region the highly strained appearance of the minerals pertaining to the early paragenesis is the most remarkable. Cataclasis and wavy extinction are common in the siderites, older quartz, ankerite and calcite. Siderite of rhombohedral shape, such as in common in the Vizille area is absent here. Only elongated, intricately intergrown crystals occur.

As to the age of the faults it should be noted that only the Chamrousse vein supplies some information. There, it is seen from the cross-sections of den Tex (1950) that the fault that has acted as a channelway for the mineralizing solutions of the Chamrousse vein has affected the Triassic alteration zone, hence, must be of post-Triassic age (fig. 73). Its young, probably post-Alpine, age can also be concluded from the content of the liquid inclusions of the quartz II phase. These inclusions of high pressure and a large liquid CO₂-phase can hardly be believed to have survived strong fault movements. The same reasoning may hold for the age of the Roche Moutas, Mollard and Vaudaine deposits in view of the considerable discrepancy between decrepitation and homogenization temperatures of the liquid inclusions of their secondary quartz phases, which is indicative of inclusions of friable nature.

7 Mineralogy and parageneses

The mineralogy and parageneses of the Allemont ores have been tabulated in a similar way as with the Vizille ores. The characters used to denominate relative quantities, stress effects, grain size and paragenesis have the same meaning. They are explained in par. 7 of chapter I.

The compilation of this table and the arrangement according to order of crystallization yielded substantially more difficulties than of the mineralized areas of the westernmost part of the Outer Zone, which is due to several factors:

- Four types of ore deposits occur
 - a. Calcite veins with minerals of the Ag-Bi-Ni-Co-type, represented by the Chalanches deposit.
 - b. Quartz-chalcopyrite-barite veins.
 - c. Siderite-ankerite-calcite veins.

d. Chlorite-stilpnomelane-magnetite veins.

These four types are difficult to correlate because of the dispersed occurrences and the rarity of more than one type in one vein.

- Recrystallization frequently occurred, the main gangue being carbonates.
- Retrograde metamorphic transformation yielded calcite-ankerite veins, which may have been intermingled with previously deposited or contemporaneous ore deposits, or may have been taken up by younger mineralizing solutions.

The sole evidence for establishing the mineralization sequence comes from the minerals siderite, ankerite and quartz.

Siderite analyses of Roche Noire, Beauregard, Malpouchié, Trois Laux and Lac Crop (fig. 94) have such a high manganese content and are so similar, including their strained appearance, that these are thought to represent the originally deposited siderite. Moreover, their analyses fit the chemical scheme of siderites occurring in the easternmost part of the Outer Zone, where they belong to a mesothermal ore suite.

The ankerite has been interpreted as directly derived from, or contemporaneous with, the original siderite. Although the ankerite thermometer should perhaps not be applied in determining absolute values (Goldschmidt, 1962), yet the high ferro-content of ankerite in equilibrium with calcite and siderite points to a high temperature of the paragenesis, an idea which is in correspondance with the mesothermal mineral assemblage of the Aiguebelle ankerites and with the idea of a primary genesis.

Far more difficult to understand are the ankerites of Chalanches, Chamrousse, Grande Bois, Beauregard, Trois Laux, St. Charles, Grande Roche and Essarts, since these are probably intermingled with dolomite of Grande Bois composition. This dolomite has also been noticed in veins that apparently have little to do with the ore mineralization, since it is associated with manganiferous calcite, epidote, asbestos, prehnite, chlorite and quartz (for instance: the Pas de la Coche vein, analysis in part II).

These dolomite-calcite-veins are very common in the Inner Zone. They generally are localized on faults or joints, or have cemented fault breccia's (fig. 76).

Since the amphiboles and garnets are of a relatively high manganese content (Kalsbeek 1962), and even rhodonite has been observed (J.R. Möckel, pers. communication), the high manganiferous ankerites and calcites in these veins may be explained as being produced by retrograde metamorphic leaching, rather than that a hypogene origin should be invoked.

The ankerites and dolomites of questionable genesis, however, occur in the same paragenetical position with regard to siderite as the Malpouchié ankerite, which means that the intermediate compositions between Malpouchié and Grande Bois, are the result of contamination of ore solutions by previously formed dolomite. It is remarkable that an inversed proportionality exists between the quantities of siderite and ankerite. Veins where siderite is almost absent are close to Grande Bois in chemical composition. Further evidence for the idea that the aberring ankerite should not be assigned a special position beyond the normal ore assemblage comes from the following up of this ankerite by a

suite of undoubted primary Co-Ni-Ag-Bi-minerals of Chalanches, and the common sequence by quartz of the same liquid inclusions content as that of Malpourchié.

The mineral assemblage of Chalanches displays a remarkable likeness to those of similar Hercynian deposits in Europe: St. Marie-aux-Mines (France, Stelzner, 1904); St. Andreasberg (W. Germany, Stelzner, 1904), Steiermark (Austria, Friedrich, 1933) and Freiberg (E. Germany). An extensive recent study of the Freiberg ores by Baumann (1958), contains mineral descriptions, sequences, and mutual replacement phenomena, that fit those of Chalanches, even to the slightest details. Schneiderhöhn (1941) has drawn the attention to the likeness of such widely scattered Co-Ni-Bi-Ag-deposits. Although Chalanches as a whole is a typical representative of this mesothermal ore type, yet recrystallization has caused a small shift from the ideal mineral compositions. The FeS-content of sphalerite for instance amounts to 6.5 mol. % for the darkest (brownish-red) sphalerite, a value which should correspond to a minimum crystallization temperature of 210°. The actual crystallization temperature presumably has been higher since the sample investigated has been completely entrapped by quartz I of a minimum crystallization temperature of 270°, and the sample also is devoid of chalcopryrite exsolution drops which otherwise are present if sphalerite is replaced by a younger mineral.

The high MnS-content (0,23 wt %, the highest recorded percentage) is concurrent with the chemical character of the Inner Zone; another MnS-rich sphalerite of Fond de France, (0,18 wt. % MnS) also occurs in the Inner Zone.

The loss of certain trace elements under the influence of younger formations, and the exsolution of compounds that are soluble in greater amounts at high temperature than at low ones, is shown by tetrahedrite that exsolves chalcopryrite and sphalerite where it is replaced by bournonite. Also galena displaying a high silver (0.09 wt. %) but low bismuth content (0.002 wt. %) has been subjected to recrystallization.

Besides ankerite quartz also enables a parallel to be drawn between the individual deposits. The type of quartz which may serve as link is of strained appearance, but not so strongly affected by mechanical dislocations as to lose its primary inclusions completely. The latter feature occurred with the quartz I phases of Chalanches, where almost all inclusions are of secondary origin and are to be attributed to younger quartz-bearing solutions, forming individual crystals elsewhere.

The inclusions retained are of a hydrothermal type, have a definite CO₂-content, and homogenize in a very narrow temperature range. The latter points to crystallization from a homogeneous solution under which condition the true crystallization temperature can only be established by applying pressure corrections, conformable to the older vein quartz of the Vizille region.

In most veins this quartz is one of the youngest formations among the older mineralization suite.

The young calcite-galena-silver formation (comparable to Freiberg's "Edele Geschicke"), is younger than and embedded in a coarsely crystalline calcite, featuring some scarce stress effects and having a lower manganese content than the old calcite affiliated to the siderite-ankerite suite. Obviously,

this silver-formation is the latest phase, and has been deposited after the main tectonic movements.

In the Vizille region we have learned to regard the younger parageneses as products of Alpine rejuvenation. This condition, however, need not to count for the formation of the lead-silver paragenesis of Chalanches, since mineralization of proven Alpine age are absent there (no young vein quartz), and part of the older paragenesis has been shown to be deposited under other geological conditions. A division of Chalanches into an older Ni-Co and a younger Ag-suite is artificial and contrary to the classic Co-Ni-Bi-Ag-ore type, of which the silver suite in all instances is the younger, post-kinematic phase.

Other veins, however, provide indications that at least some hydrothermal activity of Alpine age has occurred. Again, as in Vizille, the information comes from quartz. Its inclusion-content is similar to that of the younger vein quartz of Vizille. This quartz displays a marked depth-controlled density of the CO₂-rich phase. The density of the CO₂ phase is just critical with regard to the kind of phase transition that occurs. Some quartz crystals (La Fare, Rouche Moutas and Chamrousse) contain CO₂ phases homogenizing between 22° and 31° into a gaseous CO₂-phase, others (Vaudaine) homogenize at 31° into a liquid phase.

The pressure at crystallization from a non-homogeneous medium, has been in the order of 350 kg/cm². The veins invariably occur at high altitudes (2000-2200 m) close to the sub-horizontal Triassic covers. Some of these covers fortunately have been preserved from erosion and enable the reconstruction of the Triassic peneplain and the calculation of the amount of vertical displacement occurring along Alpine faults.

At still higher altitudes (2200-2400m), in a quartz type of presumably the same mineralization phase, inclusions are found that do not show the condensation of a liquid CO₂ phase on cooling, but contain appreciable amounts of crystallized isotropic solids (NaCl). These NaCl-containing inclusions are to be seen as higher deposited equivalents of the Chamrousse type, being entrapped from the same solution but at lower hydrostatic pressure, such that a homogeneous liquid was the sole possibility, the densities of CO₂-rich and H₂O-rich phases being too different to become statistically intermingled. Equal liquid-gas ratio's support this view. Unfortunately the homogenization test failed with the instruments available, since the rate of temperature increase needed to prevent a harmful heating of the microscope surpasses the rate of temperature increase required for complete solution of the salt. The homogenization temperature has been estimated at 260°. Because of the low CO₂ content more salts have been dissolved than was the case with the deposits from a deeper level.

The inclusion type of Chamrousse is almost identical to that of the younger vein quartz of the Vizille and Alleverd regions, if occurring within the proximity of the level of Triassic sedimentation. The host of at least some among them could be shown to be of Alpine age. The Chamrousse vein proves that this interpretation is also true for the Allemont region, since it is located upon a fault that has offset the Permian-Triassic alteration zone.

In the paragenetic position between the younger and older vein quartz the assemblage stilpnomelane-chlorite-magnetite occurs.

The position of hematite is rather doubtful, since only relics of it occur, the greater part being pseudomorphosed by magnetite. The original mineral might belong to the older suite, where it is observed in common association with barite, a paragenesis that also occurs in the eastern part of the Outer Zone.

Stilpnomelane has been shown by E. Niggli (1956) to be a common product of Alpine regional metamorphism. The more typical occurrences in the Belledonne, however, are confined to iron-ore deposits and thus need not to bear any relation to Alpine metamorphism. Its notification by Tobi (1959) and Kalsbeek (1962) has not been ascertained. Nevertheless, its formation is most conveniently interpreted as an Alpine product, because of its undisturbed appearance, its common association with calcite and younger quartz, and the low grade metamorphism commonly assigned to the Alpine metamorphism of the Outer Zone.

Stilpnomelane and chlorite only occur in veins of which siderite forms a substantial part. The metasomatic replacement of siderite proceeded by the incorporation of all manganese in stilpnomelane and all magnesium in chlorite and further more as much iron in both these minerals as their structures can absorb (the iron percentages of stilpnomelane, and chlorite rank among the highest possible). The remaining iron crystallized as magnetite.

Supergene alteration is very common with the Allemont ores. The main part of Chalanches' silver production came from fissures filled by descending solutions with native silver, gypsum, annabergite, and erythrite. Siderite has been transformed into goethite, lepidocrocite and hematite. Trois Laux and Malpourchié provide beautiful specimen of lepidocrocite, occurring in thick crusts.

8 References

Because of the nature of its main ore: silver, and the great diversity of minerals, Chalanches drew the early attention of mineralogists. Among them are many whose memory lives on in the names of minerals called after them, such as: Berthier, de Bournon, Descloizeaux, Dolomieu, Dufrenoy, Faujas, Frenzel, Groth, Haidinger, Hausmann, Hauy, Lacroix, Rammelsberg, and Schreiber. Likewise the township, in which the Chalanches mines are situated has given its name to a mineral, viz. Allemontite. One of the earliest and most detailed studies on the structural features of the Chalanches ores we owe to Schreiber. Soon after exploitation on an industrial scale was achieved, he has written his most important publication (1784), followed by some additional ones in 1786 and 1788. Only Guettard's description of a mineralogical itinerary in Dauphiné (1779) is older, but he merely enumerates the mines and their main ores. Guettard and den Tex (1950) are the sole authors who mention the Chamrousse and Vaudaine veins. Later authors, who were in the situation to perform mineralogical and paragenetical studies on the Chalanches deposit when the mines were still active, include: Dolomieu (1795) whose study also mentions the siderite deposits of the Articol area, and Hericart de Thury (1806). This description is regarded by Gueymard (1844) to be the most extensive enumeration of data on the mine and its minerals.

Until the data of definite closure of Chalanches two other authentic reports dealing with the whole deposit have been written. One by Graff (1886), who made a study of the structure of the deposit, and another by Gueymard (1844). Gueymard is the sole author who gives a detailed description of both the deposits of Chalanches and the siderite and ankerite veins of the Articol and River d'Allemont areas, dealing with the Grande Bois, Roche Noire, Malpourchié, Trois Laux, St. Charles and Lac Crop deposits. Even the small base metal deposits of La Fare, Mollard and Oulles are recorded by him. Gueymard's publication is especially valuable since many data have been preserved that are not accessible for present-day observation, because of the advanced state of decay of most mining works, such as data on the dip, strike, length, width of the veins and the mining history. Reference works such as those of Ch. Lory, (1865), Caillaux (1870), Tirloir (1878), de Launay (1895), Hintze (1904), Doelter (1911), and Demaret (1914) record what previously has been published, without adding new data. An exception should be made for the handbooks of Lacroix (1893) and Ramdohr (1960). Ramdohr has added three mineral species: breithauptite, safflorite and rammelsbergite to the number of 35 ore minerals known from Chalanches.

Publications that contain informations about the history and development of mining and metallurgy include: Chabrand (1892, 1900, 1905), Tenot (1919), Bourgin (1920), Sclafert (1926), Buffault (1936) and Blanchard (1941).

The references to publications that deal with the special mineralogy of Chalanches are listed in Part II with the minerals: allemontite, cinnabar, niccolite, safflorite, silver, and skutterudite.

CHAPTER III

THE ORE DEPOSITS OF THE ALLEVARD REGION

1 Geographical setting

The choice of the Allevard region as a district of the Belledonne metalliferous province is not artificial. Mode of occurrence and composition of the ores show a rather uniform picture, while its setting fits a geological and structural frame. Its position appears on the map. Some remarks about its eastern and western border may be added. Both are faults and have morphological evidence. The eastern border of the Allevard region is the anomalous contact between the crystalline rocks and the allocthonous Mesozoic shales and coincides with the NE-SW trending valley of Allevard and Theys.

The western border is the Median Syncline, the thrust fault between the Belledonne's Inner and Outer Zones. The position of this fault is marked by some cols between the high level central chain and the Grand Collet - Grand Rocher ridge parallel to this chain.

The Grand Collet - Grand Rocher ridge is obliquely dissected by NW streaming torrents viz: The Bens and Veyton torrents and the lower reaches of the Breda river. The northern border of the region is the Bens torrent which also forms the boundary between the Savoy and Isère departments, and until 1860, has been the frontier of France and the kingdom of Savoy.

2 Historical notes

The iron mining industry has put its stamp on the historical development of the Allevard region more than on any other part of the Belledonne.

Locality names derived from Celtic words denoting mining or metallurgical activity, such as Rafour (iron-furnace) show the early interest paid to its mineral wealth (Billaz, 1907). The most ancient written accounts date of the eleventh century and already mention the iron ore exploitation (Schafert, 1926^a).

The name of La Ferrière, St. Hugon, and Chapelle-du-Bard appear in the archives of the twelfth century as centres of mining activity. The foundation of the Carthusian monastery in the Bensvalley ("La Chartreuse de St. Hugon") dates also from this century. This convent was particularly concerned with the treatment of iron ores. Several furnaces have been constructed by them; occasionally two at a time, one in France and another in Savoy, in order to meet political difficulties. The Charthusians probably were the first to develop the process of steel fabrication in France (Bouchayer, 1927).

The mines of la Taillat, Girodet, Plan du Four, Essarts and the Merdaret are recorded in the fourteenth and fifteenth

century.

In those centuries the exploitation of the ores was confined to production from shallow excavations, mainly because of the rather primitive methods of ore treatment which hardly permitted to make use of the other ores than altered siderite.

When the outcrops became exhausted, an episode of decline commenced, and iron ore mining almost ceased in the sixteenth century (Monnet, 1927). The seventeenth and eighteenth centuries gave the picture of renewed activities, due to better furnaces attaining higher temperatures and enabling the employ of fresh siderite. Almost all traces of mining and roasting found beyond the Taillat and Croix Reculet areas date from this period. Many mines are recorded: Planchaney, Clavette, Envers, Malatrait and Tilleray of the Grand Collet area, and Rochefort, Jeu de Paume, Marameille, Genivelle, Panissière, and Violettes from the Grand Rocher-Taillat area. In 1815, the year of enactment of a new mining law, the region was sub-divided into 26 leases. The lessees were the owners of one of the three blast-furnaces, of the Allevard canton viz: Allevard, Pinsot and St. Hugon. In the latter part of that century the interest of mining and smelting of the individual enterprises have been combined into one company. This company, "Creusot", closed the smaller mines and brought the Taillat mine to high production: one million tons of ore in twenty years. In 1899 the mines and metallurgical industry became the property of the "Société des Hauts-Fourneaux et Forges d'Allevard (meanwhile the Pinsot and St. Hugon furnaces were closed down), but the deposits proved unable to compete with the newly discovered iron ores of Lorraine and Normandy. The Taillat mines have been closed in 1929, but the forges and electro-metallurgical works are still active.

3 Mining methods and exploitation data

The most elaborate mining methods have been practiced in the Taillat lease, where about 15 rich and closely spaced siderite veins occur. Among them the Taillat Rives and the Maillat veins are the main ones. They are about parallel to each other (strike S 35° E), and each of them attains a length of 600 meters and a depth of more than 300 meters. The average width of the Rives vein amounts to 3.5 meter and that of the Maillat vein to about 5 meters. Both are cut by NE directed faults, up to twenty times over.

The names of the veins were in use all over the region to denominate a certain grain size of the siderite ores: the Maillat-type designating a coarse grained texture, and the Rives-type denoting a fine siderite grain. Gueymard (1844) found, as a general rule, the fine grained siderite to be of a higher manganese content than the coarse grained type. His analyses, however, show many exceptions, which should not have happened if these names had been used to denominate a certain type of fabric, the Mn-rich Rives type for the parallel textured siderite, the Mg-rich Maillat type for a siderite of isotropic fabric.

After long periods of surface excavations and exploitation by short inclined adits and primitive shafts, the Taillat veins were opened up in 1872 by a double-track crosscut ("Galerie St.

Madeleine") to be exploited on a large scale. Pillars and parts of difficult access from above, which has been left by the surface excavations, were thus made accessible for exploitation by overhead stopping, and were shovelled down to the Madeleine level.

Later mining progressed downward, the ore being conveyed to drifts below the St. Madeleine level (1104) m, and from there to the surface or to the haulage-track by a newly constructed shaft (St. Madeleine-shaft).

In this way one million tons of 30 % iron ore have been won within twenty years. As the upward transport became a serious problem (1894) a new crosscut was driven at 900 m level: the "Galerie St. Henry". A new shaft and a rope-hauled inclined track, one from the 1100 m level to the St. Henry adit and another from St. Henry to St. Pierre d'Allevard (500 m) completed the installation. In St. Pierre d'Allevard the minerals were hand-sorted, cleaned from sulphides and treated in calcining furnaces. From there the ores were sent by railway to the blast furnaces at Allevard.

In the end of the nineteenth century the interior parts of other deposits of the Taillat-Croix Reculet leases were also won. The exploitation occurred by SE-trending drift-adits. Those of the Lavanches, Borel, and Vaugraine deposits are still visible and occur at about 1100 m level. The Grande Brache, St. Victoire, La Chaume and Pinot deposits were exploited from the Taillat Rives works.

Most tunnels in the other leases date from the early part of the nineteenth century, when Gueymard was director of mines for the Isère department. He designed many tunnels to open up deposits from below which formerly were worked by open cast methods, but had been abandoned, because of water, displacements of the ore body, or hoisting difficulties. The St. Jacques, Malatrait, St. Joseph, Ravoire, Gros Chêne, Grande Taillée, Esperance, Combe Noire and Gangrette deposits may be quoted as examples. Surface excavations of impressive depth and length such as Marameille, Lac de Bens and Clarans date from still older periods. Pines growing in the deep trenches even enable to calculate a minimum age since exploitation ceased, by counting annual growth rings. Thus Marameille is older than 200 years.

4 Geological outlines.

There is much to be said about the geology of the Allevard region, but only those features that are of interest to the ore deposits will be mentioned.

Of interest are: - the nature of the host rock
- and structural features

a. Crystalline rocks

The crystalline rocks of the Allevard region are of a rather monotonous character. They form part of the Outer Zone and mainly consist of sericite-chlorite schists and albite-sericite-chlorite schists. They are very well exposed in a section perpendicular to the general strike in the valley of the Bens river: the St. Hugon valley. Hence, they are designated by Tobi

(1959) as the St. Hugon schists. Their epizonal metamorphic grade is of a progressive nature, they have hardly attained a higher degree of metamorphism. Later phases of low grade metamorphism have therefore accomplished very little effect on them. No relation has been observed between the composition of the St. Hugon schists and the content of the ore veins.

b. Upper Carboniferous

The Upper Carboniferous sediments comprise conglomerates, black slates and tuffaceous deposits. Its lack of metamorphic effects, angular unconformity with the crystalline rocks and presence of plant imprints distinguish this formation as a marker horizon of orogenic history. Of special interest is its mode of occurrence, viz: in narrow and deep synclines cicatrizing faults. This phenomenon will be dealt with in the structural section of this chapter. The Upper Carboniferous does not occur as host rock of the ore veins.

c. Permian

A formation of arenaceous and pelitic sediments of continental facies occurring only within the region under discussion is known as "Grès d'Alleverd". Plant imprints indicate a Lower Permian age (Corsin and Tobi, 1954). Its position in orogenic history is much disputed. Re-examination of the Pierre Herse section, which has led P. Lory (1895) to assume an angular unconformity between Upper Carboniferous and Grès d'Alleverd, has brought to light that the Upper Carboniferous is actually absent. But nevertheless, the structure of the Grand Collet is such that the relation between Upper Carboniferous and Permian is most readily explained as an angular unconformity. The Grès d'Alleverd occurs as a horizontal or sub-horizontal cover on the summits of the Grand Collet-Grand Rocher ridge, but dips steeply SE near the Carboniferous syncline. Its position is autochthonous, although slickensides between the sandstone and the substratum may occur. Some ore veins continue up into the Grès d'Alleverd. Especially siderite veins do so, a disperse sideritisation of the sandstone being an accessory effect.

d. Triassic

The fact that ore veins invading the Grès d'Alleverd terminate against the Triassic strata has drawn the attention of Nicolet (1931). He explained the abutment by assuming an Upper Permian age of emplacement of the ores, since the present composition of the major part of the Triassic (viz: cavernous limestones) is such that replacement by carbonate solutions, if available, should have been very likely.

This theory, however, fails to account for three features:

- 1) Some veins tend to follow the disconformable contact between Grès d'Alleverd and Triassic (Taillat Maillat, fig. 78),
- 2) a deep alteration of the vein content near the contact does not occur, a feature that certainly should have been brought about as a result of Triassic weathering conditions,
- 3) part of the Triassic is built up of anhydrite and gypsum beds, i.e. formations that will not transmit the tensional

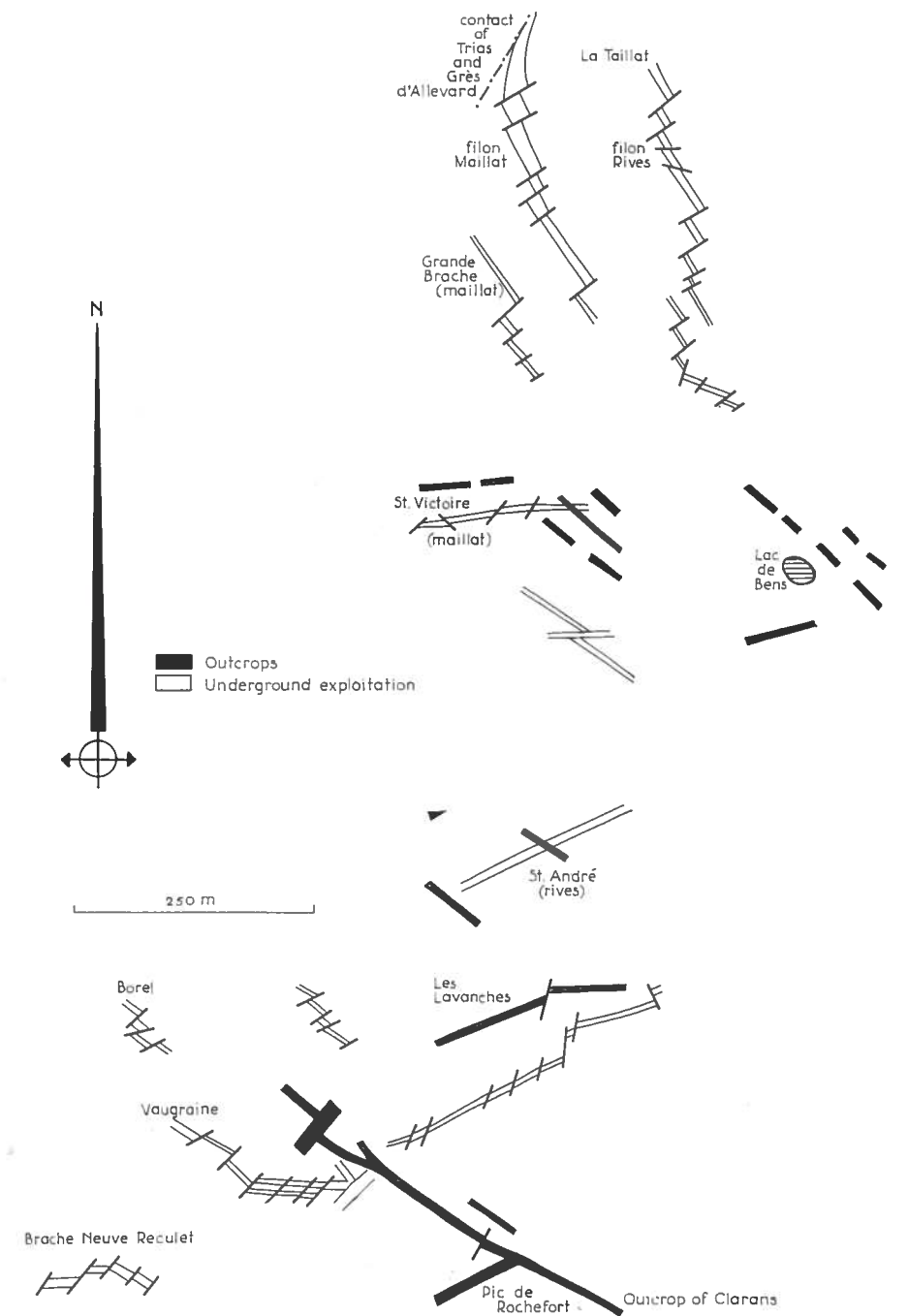


Fig. 78. Pattern of siderite veins of the Taillat area (Alleverd ore district). The Taillat Maillat vein (younger ore suite) follows for some tens of metres the contact of Grès d'Alleverd (Permian) and Triassic.



Fig. 79. View from the west to the northern part of the Allevard region and the southern part of the Aigubelle region. Both are separated by the Carboniferous synclines of Proclin (the northern most wedge) and the Grand Collet (middle wedge). The numbers refer to the ore deposits.

forces causing fissures.

Having proved the post-Triassic age of ore veins terminating against the Triassic, the question remains to be solved why they do not penetrate into the cavernous limestones. A very likely explanation is given by Brückner (1941). He found the exposures of Triassic cavernous limestones to be the stratigraphical equivalents of mixed anhydrite-dolomite deposits as met with in fresh condition in tunnels. The hydration of anhydrite to gypsum brought about a volume increment and subsequent brecciation of the dolomite compound. This process has been followed by calcitization of gypsum and, eventually, dolomite. Later weathering resulted in a selective solution of the dolomite part of the rock. Tunnels cut through the Belledonne also confirm the idea of Brückner, since the anhydrite layers appear to be of the same stratigraphical horizon as the cavernous limestones at the surface (Moret, 1952).

e. Jurassic

Ore veins or veinlets are of rare occurrence in the Jurassic sediments. It is neither the Jurassic's lithology, as is the case with the Triassic, that accounts for the scarcity of veins, nor the age of emplacement, since the Jurassic consists of calcareous shales and limestones, and because some veins actually do occur. The reason for this feature must be sought in the presence of Triassic barrier strata and in the allochthonous position of the greater part of the Jurassic, a fact that will be discussed in the structural paragraph of this chapter.

f. Quaternary

The Quaternary comprises glacial and alluvial deposits.

5 Structural geology

As many ore districts do, the Allevard region displays a close relation between structural features and mode of occurrence of the ore deposits.

a. Results of metamorphism and folding

The phenomena of the oldest orogeny: folding, development of schistosity, and metamorphism of the Outer Zone, are cut across by the ore veins, and have little or no influence on the content or on the shape of the veins. They brought the basement of the Belledonne Range into its present crystalline state.

b. Emplacement of granite and wrench-faults

The character of the Belledonne has been thoroughly changed by the intrusion of granites and a penecontemporaneous development of a wrench fault system during the later stages of consolidation of the magma.

The wrench fault system has produced an extension of the Belledonne Range in a NNE-SSW direction as a result of a ESE-WNW directed compression.

The position of the faults and their amount and sense of heave are very evident in the Inner Zone. Although the Outer Zone has been subject to the same compressive stresses as the Inner Zone, the presence of a wrench fault system is difficult to establish there because of the lack of marker beds and the monotony of the Outer Zone schists. Its presence may be indicated by the relationship between the strikes of faults and ore vein pattern (viz: feathering out from the wrench faults directions). The latter feature, however, does not constitute proof of equal age of veins and wrench faults, since the fault and joint pattern may have been rejuvenated by the Alpine orogeny.

c. The Median Syncline

The Median Syncline is an example of such Alpine rejuvenation of fault and shear zones. The discontinuity upon which the Median Syncline is located, is contemporaneous with the origin of the Belledonne as a structural and geological entity. Through late Hercynian and Alpine tectogenesis it has grown into its present state: a deep and tightly compressed syncline filled up by intricately intermingled Liassic, Triassic and Upper-Carboniferous sediments.

The quantity of the pinched-in sediments is very variable. The cross section of the Median Syncline, near the point where it traverses the Grand Collet - Grand Rocher ridge, shows a thoroughly intermingled mass of Upper Carboniferous and Triassic gypsum of about 400 meters width, whereas a few kilometers north of this point the Median Syncline is completely devoid of its sedimentary content, being merely a scar.

The dip is gentle: 30° to SE, the strike N 100° E. The thrust plane is also a plane in the geometrical sense of the word. Its position can be constructed with the data of the position of three of its outcrops (Kalsbeek 1962, Touwen 1959). A few ore deposits occur in the sedimentary rocks of the Median Syncline, and hence, give evidence of mineralization of Alpine age.

d. The NNE-trending Carboniferous syncline of the Grand Collet

The Grand Collet area possesses underneath its cover of Grès d'Allevard and Triassic a steeply dipping, tightly compressed syncline of Upper Carboniferous rocks (fig. 79). The eastern flank of the syncline is bordered by a fault with a throw of E-block upward. The W-block is tilted westward and its sedimentary cover gently dips to the west, but deviations of the general dip occur as a result of folding and small parallel faults. The faults, the bedding of the Carboniferous and the schistosity of the Outer Zone schists have an equal strike (fig. 8).

e. Some minor faults

The tectonic features mentioned above (wrench faults, Median Syncline, and Carboniferous synclines) have divided the Belledonne into a number of lenticular blocks. They are of Hercynian origin but have been rejuvenated during the Alpine orogeny, as shown by their enclosure of Mesozoic and Permian rocks. The confinements of these lenticular blocks coincide with the boundaries of certain ore districts, within which definite

ore types prevail. Mineralization of the main faults themselves is rare.

Within these blocks other faults occur. They are of two types:

- A. parallel to the schistosity
- B. perpendicular to the schistosity

Among the parallel type have to be mentioned:

A. 1. The NNE-trending Beauvoir fault

The geological map of the Grand Collet area, made by Touwen (1959), shows a wedge shaped mass of Triassic pinched into the Outer Zone schists near Beauvoir giving evidence of an approximately NNE-SSW trending fault. Since index horizons are lacking in the Outer Zone schist, the continuation of the fault to the south is difficult to establish. It is remarkable, however, that assuming a NNE-SSW trend, the crystalline schists east of the fault are covered by a 200 meter thick mantle of Grès d'Allevard, whereas the western counterpart is devoid of it. The feature that this fault is the northern and eastern limit of the mineralized area is worth mentioning too.

A. 2. NNE-trending faults of the Pierre Herse

A cross-section of the Pierre Herse torrent, published by Tobi (1959), reveals the existence of faults parallel to the general schistosity.

Of the perpendicular type are:

B. 1. The SE-NW fault of the lower Breda gorge

Where the Breda river emerges from the crystalline part of the Belledonne into the valley of Allevard, the river passes through a narrow gorge. This gorge is assumed to be moulded upon a fault since the geological section of the left bank does not meet that of the right bank (fig. 81). The relative movements of the north and south blocks are difficult to establish. The author thinks the north block to have been thrown upward because of the steeper slope of the contact between crystalline basement and Grès d'Allevard.

B. 2. The ESE-WNW fault of the Merdaret brook

This fault shows a throw of the south block upward.

The faults parallel to the schistosity generally dip 90°-60° to east, the oblique or perpendicular ones are about vertical. The main faults are only rarely mineralized.

f. The "décollement" of the Mesozoic cover

The youngest feature to be mentioned is the gravitational gliding of the Mesozoic cover from the Belledonne's western-slope.

The cross section of the Chapelle-du-Bard torrent displays the situation (fig. 80). In order to understand this section one has to discriminate between two features:

- a. the sliding downward of the bulk of the Mesozoic mass, and
- b. the effect of the "dédollement" on the sedimentary cover remaining attached.

The first feature resulted in a simply folded range of hills with rather steep schistosity: the "Collines Liasiques".

The Triassic gypsum beds have served as lubricating layers. A tunnel through one of these hills (Brame Farine) has revealed complexly intermingled masses of gypsum in the Liassic shales.

The load of the downsliding nappe caused a folding of the attached Mesozoic cover. These folds have a subhorizontal axial plane and ditto schistosity. The underlying Permian did not take part in the plastic deformation but reacted by subhorizontal faulting.

The Triassic beds enabled the Lias to become folded over a rigid basement. It has filled up the anticlinal structures and almost completely has been pressed out of the synclines. Strong deformation took place in the lowermost horizon of the Lias: the Rhetian. It has been stretched extremely as shown by the boudinage of intercalated limestone beds in the Bout-du-Monde section.

Another particularity shown by this section is the presence of a fault in the crest or the anticline, which caused a sliding downward of the upper limb (fig. 81). This limb, covering the complexly folded Lias and Triassic, will be inferred to have a close relation to the presence of a hydrogen sulphide-bearing mineral spring.

6 The mineral spring of Allevard

Allevard owes a great deal of its touristic attraction to the mineral spring. This spring is situated in the Breda gorge close to the river. An analysis of the waters reveals next to considerable amounts of hydrogen sulphide, carbon dioxide, and carbonates and sulphates of sodium, calcium and magnesium, traces of iron, manganese, zinc and arsenic.

Inhalations of cold or hot vapour are taken for the treatment of bronchial and pulmonary diseases.

From a geological point of view it is interesting to note that the slipped-down upper limb of the horizontally folded Lias (mentioned above) serves as a cover of a subterranean rain water reservoir and enables the water to circulate long enough to dissolve appreciable amounts of carbonates and sulphates from the Triassic beds. The nearby presence of siderite and tetrahedrite ore veins is the source of the trace-element content of the spring. Upon percolation through the Liassic shales the sulphate ions of the acid mineralized water become reduced to sulphides through the action of organic matter.

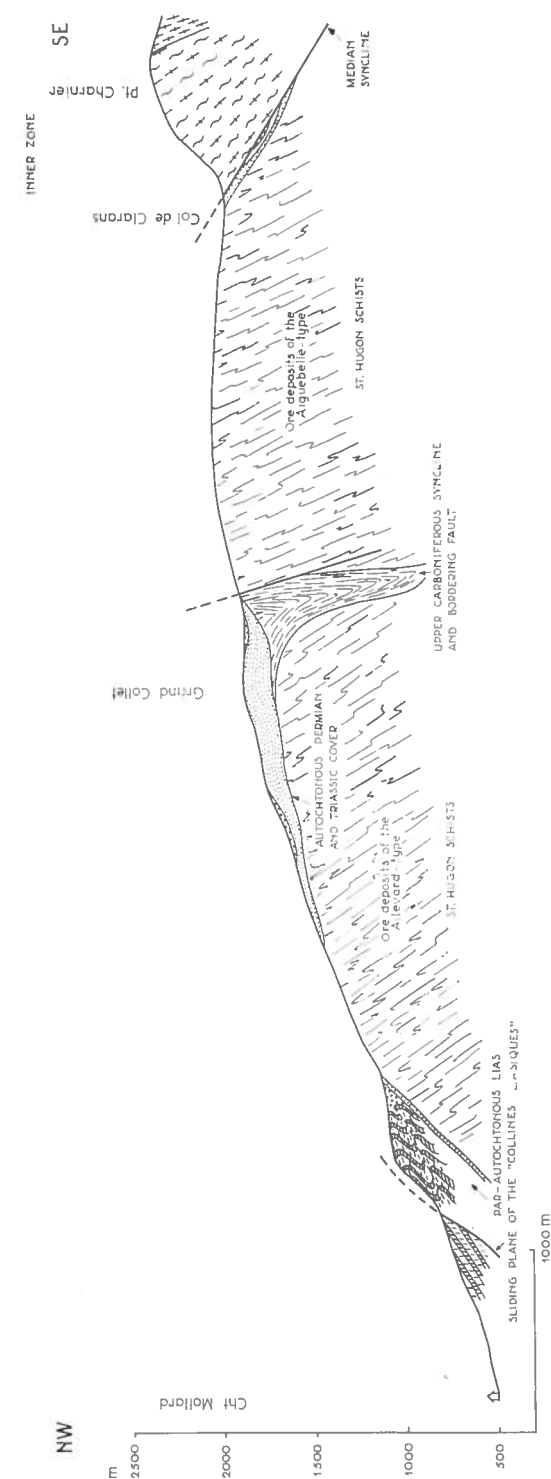


Fig. 80. Section through the Grand Collet. According to data of Touwen (1958) and personal observations.

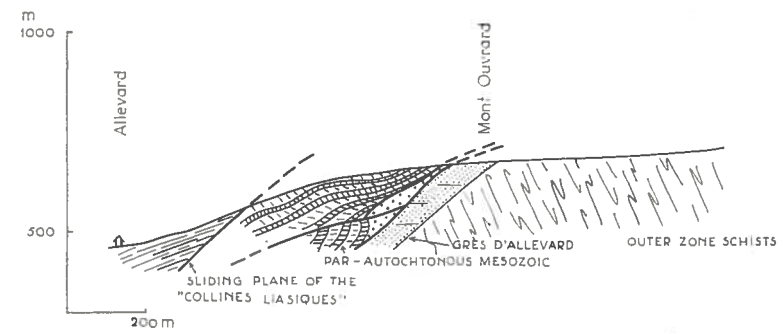


Fig. 81. Detail of the par-autochthonous Mesozoic cover such as displayed by the Bout du Monde gorge of the Bréda river. The formation marked by widely spaced dots represents the Triassic (gypsum, dolomites and limestones).

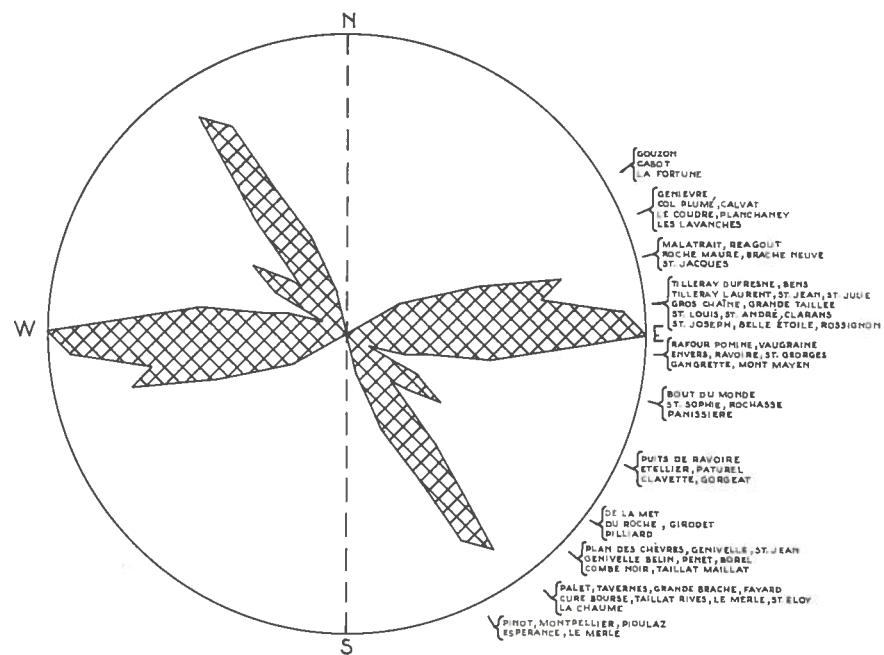
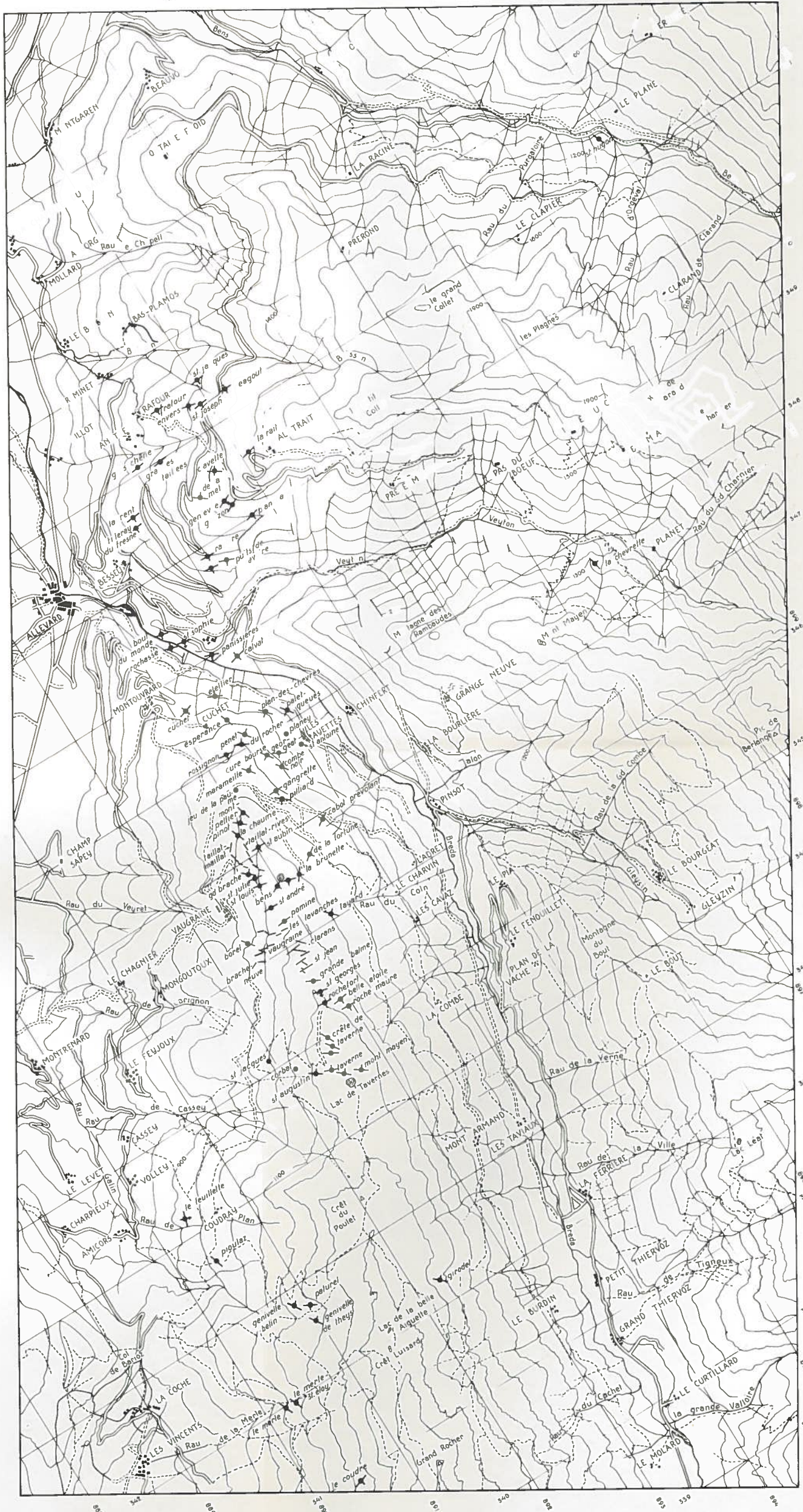


Fig. 82. Diagram of strikes of the ore veins of the Allevard region.



7 Shape and structural features of the ore deposits

A close relationship exists between the nature of the wall rock and the mode emplacement of the ore mineralization. Ore deposits occurring in the crystalline schists and the Grès d'Alleverd generally are of vein type. Occasionally the Grès d'Alleverd also shows a disperse or ramified kind of mineralization. In the Triassic and Liassic sediments, however, replacement phenomena prevail.

The general picture of the vein type deposits is that of a steeply dipping fissure vein, of about $\frac{1}{2}$ -7 meters width and 20-100 meter length reaching depths of one or several hundreds of meters and ending upwards in a wedge shape (if occurring in the crystalline rocks) or into numerous ramifications (if occurring in the Grès d'Alleverd), or abutting against the Triassic gypsum, anhydrite or cavernous limestone beds.

Most veins are cut, once or several times by NNE trending faults, a direction that is approximately parallel to the main thrust faults and to the overall schistosity (fig. 78).

A diagram (fig. 82) based on 80 strike measurements of the Alleverd ore veins reveals that the trend of the major tectonic features (Median Syncline and wrench faults) is, as a rule devoid of ore mineralization. This is a common feature in ore districts. The normal stresses acting on such fault or thrust-planes have been prohibitive for the intrusion and deposition of ore matter.

Much more appropriate for mineralization are tension joints and fissures belonging to the stress pattern. In the Belledonne, too, the trend of the ore veins is such (Wolfson, 1960) that they may be interpreted as forming part of the feather-joints of the wrench fault system (fig. 83).

This interpretation implies that the Outer Zone has also been affected by a wrench fault system, which does not stand out clearly in the field, however. The presence of such a fault system, is very likely in view of the fact that the Outer Zone must have been subject to the same stresses as the Inner Zone.

Not all ore veins are of equal age. A study of the ore content and structural considerations have led the author to assume at least two periods of mineralization.

On the strength of their content two types of ore veins are easily discerned. One is characterized by manganese-rich and magnesium-poor siderite with an intricate fabric and accompanied by sulphides of an essential trace-element content occurring together with cataclastic and strained quartz, the latter only scarcely showing liquid inclusions.

The other type consists of magnesium-rich randomly textured, coarse-grained siderite, with a sulphide content of a rather simple composition and accompanied by strain-free quartz, possessing many three-phase inclusions.

The latter type is the younger, as shown by the Bout du Monde deposit, where both types occur in one vein (the younger inside the older) and the Taillat area where the older type is cut obliquely by veins possessing the mineralogical characteristics of the younger type.

A comparison between the veins of the younger type with veins occurring in formations of Alpine emplacement (viz: the Median Syncline and the Liassic replacement deposits) even enables a

lower age limit to be set for this type: i.c. post-Liassic.

More indications for an Alpine age of the younger paragenesis are obtained from:

- The presence of quartz with large three-phase inclusions, containing liquid CO₂ under pressure in the sedimentary content of the Median Syncline and in mineralized faults affecting the Triassic. This speaks even for a post-Alpine age.
- The course of veins cutting crystalline schists as well as Grès d'Alleverd but having been left unaffected by this contact, notwithstanding the common presence of slickensides between both formations.
- On reaching the contact between the Grès d'Alleverd and the Triassic the Taillat Maillat vein is seen to curve around, following the contact for some tens of meters and then to taper out against the Triassic anhydrite, fig. 78.

In relation to the latter feature it is appropriate to recall here the behaviour of the Le Vent vein in the Vizille area on reaching the imaginary contact between crystalline rocks and Triassic, viz: the considerable dilatation, and augmentation of caved-in wall rock fragments. This feature has been explained as the result of the inability of the Triassic gypsum and anhydrite beds to transmit tensional forces up into the overlying strata, a situation in which a fissure will react as if reaching the terrestrial surface.

Similar phenomena occur in the Alleverd region, and as far as observed, only veins of the younger paragenesis diverge into numerous ramifications close to the Triassic palaeo-surface or abutt abruptly against it.

Having demonstrated the existence of two periods of mineralization of which the younger has an Alpine or post-Alpine age and the older is penecontemporaneous with the consolidation of the probably Hercynian granite, one is still not able to distinguish any difference in vein trend between both parageneses, although Hercynian and Alpine directions of stress have differed some five to ten degrees.

Apparently the rejuvenation of Hercynian dislocations has brought about the same set of feather joints that occurred during the older orogeny, a conclusion which is in agreement with the presence of a post-Mesozoic wrench fault system in the "Chânes Subalpines" of about the same trend as the wrench faults in the crystalline basement of the Belledonne.

Although no structural control appears to exist distinguishing the older paragenesis from the younger one in the way of trend, another important structural phenomena remains to be mentioned.

It is the feature that the veins belonging to the younger type only occur close to the Triassic strata, or, in case the Triassic is absent, close to the Triassic peneplain as far as this surface can be reconstructed from morphological or structural data. It may be recalled here that as a consequence of the young morphology the position of the Triassic peneplain approaches the present landscape surface very closely.

The distribution of the veins of the older paragenesis is less restricted. They occur at rather arbitrarily situated levels, but prevail, as a general rule, in the deeper parts of the mountain range.

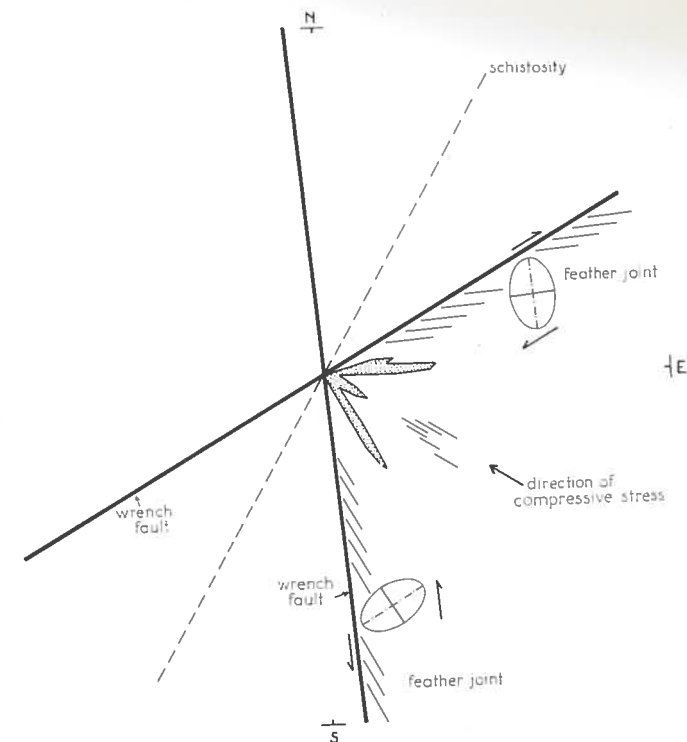


Fig. 83. The strikes of ore veins of the Alleverd region as tension joints of the wrench fault system.

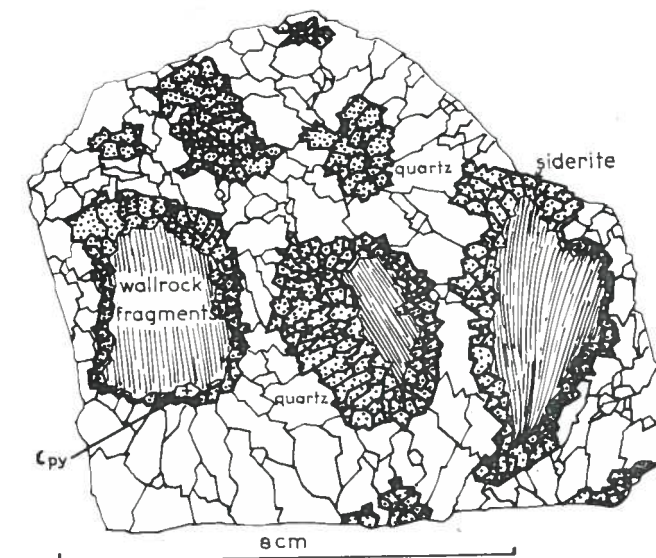


Fig. 84. Cockade texture demonstrates the age relations of siderite (intricately intergrown) and quartz. Cabot, 1 x.

8 Mineralogy and paragenesis of the deposits

The Allevard region is of similar geological situation as the Vizille region, and its mineralogy is also much alike. Again we may distinguish between an old suite of sulphides and Mn-rich siderite terminated by a strained quartz with inclusions of low gas content and uniform homogenization temperatures and a young assemblage of the same mineralogy, but of impoverished chemistry, terminated by quartz containing large liquid gas filled inclusions of rather arbitrary homogenization temperatures. The mineralization sequence of the old suite appears from cockade ores (fig. 84).

Because of the abundance of material available in this region some refinements can be made in the general picture. The sequence of the younger and the older paragenesis is more obvious here than in the Vizille region, since both mineralizations may occur in the same vein (the younger one inside the older) as at Bout du Monde, Grande Taillée, Rochefort and Tavernes or they are so closely spaced that their age relations appear from vein intersections.

It is indeed remarkable that these multiple veins contain siderite of a composition that is intermediate between those of the two types (diagram of fig. 85). Apparently part of the previously deposited siderite has been incorporated into the solution yielding the younger siderite.

For all other veins there is a considerably large compositional gap between the two siderites. Transitional types do not occur, a fact which also applies to the sulphides of either type of vein.

The exsolution of chalcopyrite from sphalerite (Gros Chêne, Ravoire) and the silver content of galena (Tilleray: 0.09% Ag) point to a mesothermal genesis of the older suite. The younger paragenesis, on the other hand, is devoid of exsolution phenomena: Taillat Maillat, Pierre Herse, and Vaujalaz.

Recrystallization, however, of the old minerals may accomplish an obliteration of the differences which originally existed between both. Gros Chêne, for instance, shows an intricately intergrown mass of tetrahedrite, sphalerite, galena and exsolved chalcopyrite. Structural etching of the specimen reveals distorted twin lamellae of the larger crystals embedded in a finely ground matrix. This type of fabric is totally different from that of the Ravoire vein situated nearby, where recrystallization occurred and chalcopyrite and sphalerite have been exsolved to constitute individual masses. This yellowish-brown spalerite has a FeS-content ranging from 5 to 5.4 mol. % FeS, and although not supporting a mesothermal genesis ($> 180^\circ$), it is substantially higher than the FeS-content of the Pierre Herse and Vaujalaz deposits, ranging from zero to 2.3 mol. %.

Also the chemical composition of Taillat ankerite shows the affiliation of the older paragenesis to the mesothermal type, because of similarities with experimentally produced ankerites of high temperature (Rosenberg, 1959). Here too, recrystallization may cause a chemical shift through the loss of Ca and Fe such as displayed by the Ravoire and Plan de Chêvres deposits.

The range of homogenization temperatures of quartz terminating the old mineralization is remarkably small (fig. 86) and thus

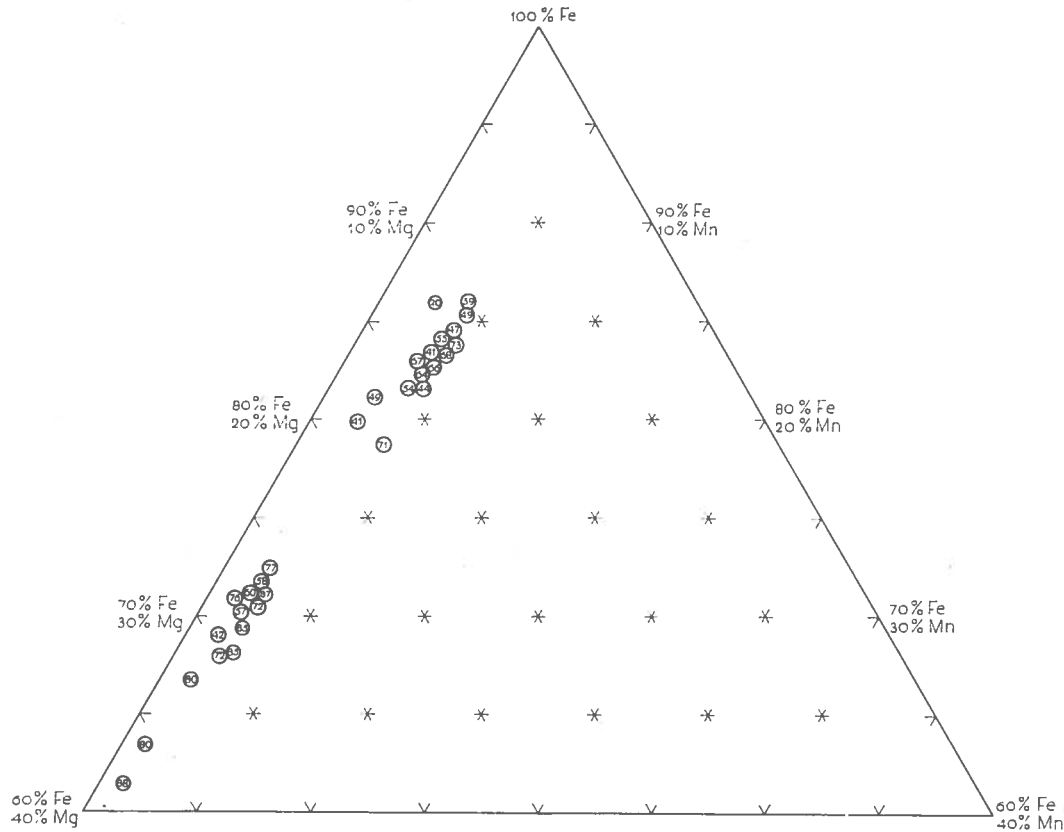


Fig. 85. Diagrammatical representation of the chemical composition of the siderite deposits of the Allevard region.

gives evidence for crystallization from a homogeneous medium. For inferring the true crystallization temperature from the homogenization temperature pressure corrections have to be applied.

The crystallization from a homogeneous medium implies that more attention should be paid to existing differences in homogenization temperature than should be done for inclusions having entrapped heterogeneous matter. Temperature differences actually do exist. The westernmost old quartz veins, occurring at low altitude and close to the gliding plane of the "Collines Liasiques", such as the Bout du Monde, St. Sophie, and Esperance veins, are almost negative for the gas test, and have low homogenization temperatures (in the 250° - 260° range). The easternmost deposits, on the other hand, occurring at high altitudes, display higher gas contents, which even may be observable as liquid gas when cooled below 31° (gaseous homog.) and consistently higher homogenization temperatures (290° - 305°), such as the Envers, Clavette, Gangrette, Rochefort and Tavernes deposits. Both extremes are linked up by quartz inclusions of varying gas content and homogenization temperatures in the 270° - 280° range. Inferring the pressure at the moment of homogenization from the course of the isochores for a system of low (for inst. 2.5 mol. % CO₂) and moderate (for inst. 6 mol. % CO₂, fig. 32) gas content it appears that the homogenization temperature of the easternmost (interior) deposits corresponds with a higher pressure than those inferred for the westernmost deposits, the pressure difference being in the order of 150 kg/cm². This means that although now occurring at higher altitudes the eastern deposits were formed at a deeper level than the western ones.

It may be interesting to compare these results with those obtained from the younger vein quartz, which occurs under almost the same conditions as the old vein quartz, both being very closely spaced to each other.

Fig. 86 shows the range of homogenization temperatures to be very broad, which apart from compositional differences, is largely due to entrapment of non-homogeneous mother fluids, as has been pointed out in chapter I of part I. This means that the pressure at the moment of homogenization equals the actual crystallization pressure. Thus the younger vein quartz of Bout du Monde has crystallized under a pressure of about 450 kg/cm². The old vein quartz, on the contrary, occurring in the same vein has inclusions of an inferred crystallization pressure of about 200 kg/cm², but crystallized from a homogeneous medium and thus permits a pressure correction to be applied. If both ore suites crystallized under the same geological conditions a pressure correction of about 250 kg/cm² should be applied, and this should also be done for the easterly situated old vein quartz. The total pressure under which this quartz has crystallized should then amount to 600 kg/cm², a figure which is incompatible with the homogenization pressure of the younger vein quartz occurring in its immediate vicinity, the latter being in the order of 350 kg/cm². The differences between both values are too significant to be attributed to inaccuracies of determination.

This observation supports the idea that the older and the younger ore veins are to be attributed to two individual mineralizations each happening under a distinct set of geological

ORE DEPOSITS OF THE ALLEVARD REGION I

Location	Altitude	Mineralogy	Fe/Mn ratio	Notes
41 Bout du Monde	349.5; 893.3 alt. 490 m	ANKERITE, BARITE, siderite II, quartz II, chalcopyrite, tetrahedrite, pyrite	23	Prim. incl.: 23 260-280 (2→1)
42 Allevard	349.6; 893.2 alt. 480 m	HEMATITE, siderite, ankerite	43	Impregnates the Grèn d'Allevard. Sample contaminated by ankerite.
43 Rafour	351.4; 894.5 alt. 980 m	siderite	40	
44 Envers	351.3; 894.8 alt. 1100 m	CHALCOPYRITE, siderite, QUARTZ	24	Prim. incl.: 10 22 7 280-290 (2→1)
45 St. Joseph	351.3; 894.0 alt. 1150 m	siderite	38	
46 Reagout	351.3; 895.0 alt. 1220 m	siderite	42	
47 St Jacques	351.4; 895.0 alt. 1060 m	CHALCOPYRITE, siderite, QUARTZ	22	
48 Gros Chêne	351.0; 894.0 alt. 840 m	CHALCOPYRITE, SPHALERITE, TETRAHEDRITE, BOULANGERITE, GALENA, siderite, QUARTZ	27	Represent a reaction series Galena caused the bordering sphalerite to exsolve chalcopyrite.
49 Grande Tailée	351.0; 894.3 alt. 930 m	SIDERITE I, QUARTZ I, siderite II, quartz II	21	Notwithstanding effects of stress, yet large prim. incl.: 22 22 7 280 (2→1). Sec. incl. are identical to the prim. ones of
50 Tilleray	350.6; 893.7 alt. 820 m	CHALCOPYRITE, GALENA, siderite, QUARTZ	20	Chemical anal. and isotope composition mentioned in Part II. Fe/Mn ratio (57) is not representative for this type of sid. because of advanced stage of alteration and leaching (no Mg)
51 de la Met	350.5; 894.4 alt. 1150 m	GALENA, siderite, QUARTZ	20	
52 Clavette	350.7; 894.7 alt. 1210 m	SIDERITE, QUARTZ	24	Prim. incl.: 23 23 30 (3→2) gaseous 280(2→1). Few stress effects.
53 Malatrait	350.6; 895.1 alt. 1360 m	QUARTZ I, siderite, quartz II	39	Prim. incl.: 22 22 7 265 (2→1) Fe/Mn ratio of a sample of another part of the vein: 42. Replaces quartz I
54 Ravoire	349.8; 894.2 alt. 950 m	CHALCOPYRITE, SPHALERITE, TETRAHEDRITE, ANKERITE, GALENA, siderite, QUARTZ, PYRITE	20	According to the analyses the recrystallized sphal. contains less FeS and chalcop. than the prim. one. Fe/Mn ratio sider.: 20 Fe/Mn ratio anker.: 21 Both are thought to be of equal age. Replacement of chalcop. by sider. is accompanied by the formation of sec. millerite
55 St. Sophie	349.3; 893.4 alt. 500 m	CHALCOPYRITE, siderite, QUARTZ	23	Small incl. prim.: 22 22 280(2→1)
56 Panissière	349.0; 893.6 alt. 500 m	siderite	38	
57 Etellier	348.6; 893.5 alt. 700 m	siderite	39	
58 Cuchet	348.6; 893.1 alt. 780 m	siderite, chalcopyrite, tetrahedrite, pyrite, quartz	35	Partly unduly. Prim. incl.: 22 22 7 280-325 (2→1)
59 Esperance	348.4; 893.4 alt. 870 m	CHALCOPYRITE, siderite, QUARTZ	22	Inclusions have a opaque coating on their walls, a feature commonly shown by quartz of this phase. incl. 22 22 280 (2→1)
60 Rossignon	348.1; 893.2 alt. 990 m	QUARTZ I, siderite, quartz II	43	Prim. and sec. incl. grade into each other: 10 22 31 (3→2) gaseous 300* 270-340 (2→1)
61 Maramelle	347.8; 893.3 alt. 1050 m	siderite, quartz	54	Displays a series of obviously prim. incl. ranging from small isometric to large concavely shaped ones: 15 22 31 26(3→2) 265(2→1) 350 (2→1)
62 du Rocher	348.1; 893.4 alt. 1010 m	siderite, quartz	32	Incl. of the same type as those of Maramelle. 22 22 31 (3→2) few still are at 355 of two phases
63 Plan de Chèvre	348.2; 893.8 alt. 780 m	SIDERITE, QUARTZ, ankerite	20	Prim. incl.: 23 23 280 (2→1)
64 Combe Noire	347.6; 893.7 alt. 900 m	SIDERITE, QUARTZ, ankerite	21	Small zonally arranged incl.: 22 22 7 270 (2→1)
65 Gangrette	347.4; 893.5 alt. 1010 m	SIDERITE, QUARTZ	24	Prim. or sec. nature of inclusions is difficult to ascertain. All are arranged in rows: 23 23 290 (2→1)

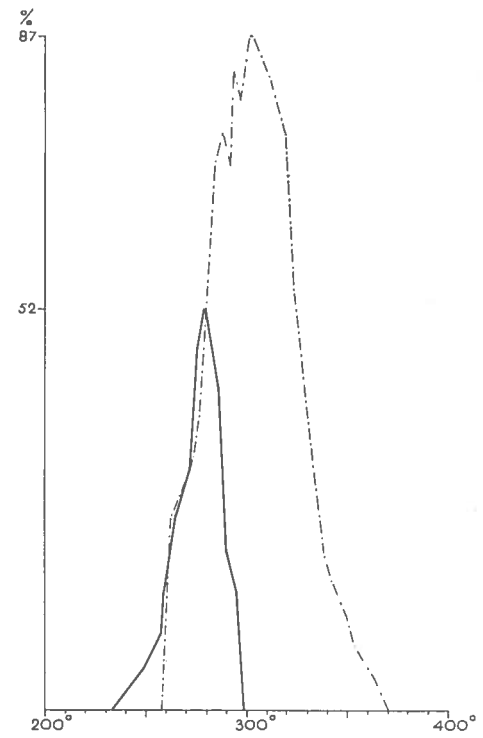


Fig. 86. Frequency of homogenization temperatures of the older and the younger (interrupted line) quartz formations of the Allevard region.

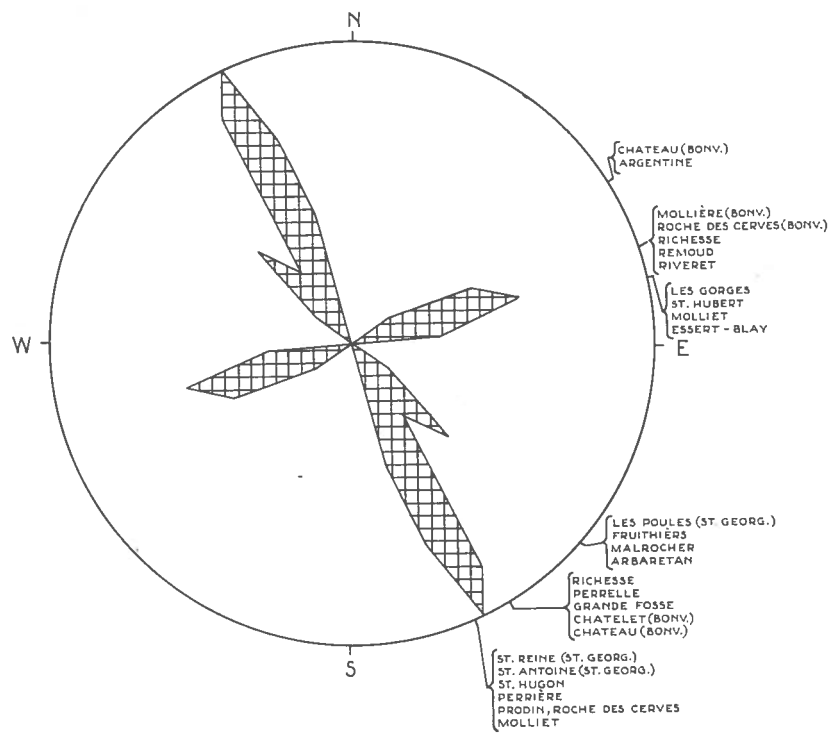


Fig. 87. Diagram of strikes of the Aiguebelle ore veins.

conditions.

The sole pressure parameter for which the young vein quartz seems susceptible is the position of the Triassic unconformable contact with Permian or crystalline schists. Close to this contact the inclusions feature lower densities of the CO₂-content, the latter homogenizing into a gaseous phase (St. Joseph, Malatrait, Maramelle, Paturel and Vaujalaz), than further away from this contact. As the distance to the Triassic peneplain grows greater, the density of the CO₂-rich phase also increases. Besides an intermediate stage of the sudden disappearance of the liquid CO₂-vapour phase boundary (Girodet), the CO₂-rich phase homogenizes into the liquid CO₂-phase. This increment of density is accompanied by a larger percentage of CO₂, higher pressures permitting more CO₂ to be solved.

The relation with regard to the position of the Triassic peneplain is such that the younger vein quartz is certainly post-Triassic for age, a conclusion also arrived at from structural observations. This is in agreement with the feature that veins to which the younger quartz belongs protrude into the Permian Grès d'Alleverd and are not offset by the contact between Permian and crystalline basement rocks. Apparently diagenetic alteration and metamorphism (Dondey, 1960) have rendered the Grès d'Alleverd compact enough to behave on tectonic dislocations in a similar way as the crystalline basement.

Returning to the older vein quartz, it has been shown that the distribution of crystallization pressures is not in correspondance with the position of the Triassic peneplain, and thus gives evidence of a pre-Triassic age of the older mineral assemblage. Although it is known that the easternmost deposits have been covered by thicker Permian formations than the western ones (ranging from 20-200 meters), the thickness of the Grès d'Alleverd has not been great enough to account for the crystallization pressure or pressure differences, even if the sedimentary load is completely calculated as lithostatic pressure, an assumption which in itself may be erroneous. The greater part of the Permian, however, may have been removed by late-Permian or Triassic erosion. Thus a Permian age cannot be excluded. Veins of the older paragenesis actually do not occur in the Permian formation but appear to have arrested a hundred or more meters from its base. If a pre-Permian age is assumed one might suppose a strong supergene alteration to have occurred in deposits so close to the abrasion surface. Actually the mine maps of the Taillet lease do not record alteration to any large extent in the deeper parts of the mines (the high-level alteration is recent). Possibly the replacement of siderite by "folded" masses of specularite, occurring in veins of the old paragenesis situated near the base of the Permian, is a result of this alteration.

Besides quartz the other mineral content of the younger paragenesis is also quite characteristic. The younger siderite does not show any stress effects, and has such a narrow compositional range that it marks the ore suite of which it forms part as a individual mineralization phase, and distinguishes it from a mere recrystallization of an older vein. The siderite compositions are diagrammatically represented by fig. 85. The sole compositional shift within this group occurs

with the southernmost siderites.

Here, the older paragenesis is totally absent, which may be due to the an increased thickness of the Permian sediments. This implies that the younger siderite has been uplifted to relatively higher levels than occurred with the ore deposits around Allevard. By this process differentiation of the chemical composition also progressed further in the direction of loss of manganese and gain of magnesium.

The sulphides pertaining to the younger mineralization have low contents of those trace-elements that are characteristic of the meso-thermal paragenesis (Ag, and Bi of galena, Fe of sphalerite). Galena of the Pierre Herse deposit, for instance, has 0,03 % Bi and 0,04 % Ag, but showed on mass-separation considerable amounts of the 205 isotope: thallium, an element which is typically concentrated in epithermal or regenerated deposits (Schroll, 1955; Baumann, 1958; Novak, 1962).

It may thus be concluded that the Allevard region has been mineralized in two stages, one of late- or post-Alpine age and another of pre-Triassic age.

9 References

Most literature on the Allevard region dates from the nineteenth century and the early part of this century, a period in which the mines were still in an active state. Most european textbooks on mineralogy or ore deposits, published at that time, mention the siderites of Allevard (Lacroix, 1893; Hintze, 1904, and de Launay, 1913). Their data are mainly based on the comprehensive study of Gueymard (1844) on the geology and ore deposits of the Isère department, of which Allevard forms part.

Besides the results of chemical analyses on siderite (Collet-Descotils, 1806; Berthier, 1828; Gueymard, 1839; Carnot, 1890 and Camous, 1905), ankerite (Arsандаux, 1901) and chalcopyrite (Berthier, 1839) no new data have been added. This also holds true for the regional studies on the ore deposits of the French Alps as performed by Gueymard (1857), Caillaux (1870), Tirloir (1878), de Launay (1895) and Demaret (1914).

From the descriptive point of view there is a great difference between the ore deposits of the French Alps and those of Germany, since the ancient publications on the Harz and the Freiberg deposits are quite informative on the subject of types and relative ages of the mineralization sequences, which cannot be said of those on the Allevard region.

Gueymard's study being the most recent complete record of mining and ore deposits, the greater part of information on names and situation of veins and leases comes from him. However, maps are lacking in Gueymard's work. Fortunately the archives of the "Société des Hauts-Fourneaux d'Allevard" keep complete maps of almost all workable deposits of the 25 mining leases. These archives also contain many documents about the mining history (purchases-deeds of works). Even titles dating from the fourteenth century are present.

The historical literature on mining activities in the Allevard region is abundant (Guettard, 1779; Küss, 1885; Pilot, 1887; Bilaz, 1907; Tenot, 1919; Bourgin; Sclafert 1926^a and 1926^b; and Monnet, 1927.

Papers dealing with the technical aspects of siderite and its treatment in the furnaces include: Du Bosc, (1815); Berthier (1820) and Gueymard (1840).

Sclafert's studies are also informative on this subject.

More recent studies on the Allevard ores come from Nicolet (1931). The latter is a thesis dealing in particular with the Taillat veins and has been written in a period that the mines were still easily accessible. The latest publication is from Huttenlocher (1934). It is a review of the ore mineralization within the western Alps.

CHAPTER IV

ORE DEPOSITS OF THE AIGUEBELLE REGION

1 Geographical setting and morphology

The Aiguebelle region is the most extensively mineralized area of the Belledonne. Like the Allevard and Vizille areas it forms part of the Outer Zone of the Belledonne, in particular its easternmost part. The geological boundaries are, in part, morphologically expressed.

The eastern boundary, the Median Syncline appears in the landscape as a NE-SW trending train of cols between the rough high mountain ridge of the Inner Zone and the high level plain of the Outer Zone. The latter is repeatedly dissected by NW-SE trending brooks and rivers. This picture is rendered more complicated by the N-S trending rivers Arc and Isère, dissecting the mountain ridge with their deep broad valleys. Immediately north and south of these rivers the position of the Median Syncline appears from brooks concurrent to the fault contact.

The western border consist of the NNE-SSW trending Upper Carboniferous syncline of Rambaudes, Grand Collet and Prodin, which submerges to the north under the "Collines Liasiques". The southern continuation of this syncline disappears in the Breda valley. This border has little morphological evidence. Where it submerges under the Lias, the western border is continued by the disconformable contact between crystalline schists and the Liassic border hills. This contact starts as a valley (Gelon valley), but to the north it also loses its morphological expression, becoming merely a discontinuity in the slope of the Grand Arc near Bonvillard.

To the south the region terminates near Fond de France in a wedgeshape between the eastern and western boundaries. To the north the region loses its mountainous character and gradually submerges under the Belledonne's par-autochthonous Mesozoic cover.

2 Historical notes on the ore deposits

Mining played a prominent part in the history of the Aiguebelle region. Apart from the legendary tales of mining activities by the Saracens and of the passage of Hannibal through the Arc-valley, "purchasing" in the Aiguebelle region new, locally produced weapons (Polybius), the oldest record of mining dates from the fourteenth century, mentioning the St. Georges des Hurtières deposits. The latter is far out the largest deposit of the area (Chabrand, 1900).

In the sixteenth century mention has been made of the smelting furnaces for lead and silver in Bourget-en-Huille and Randens, between Argentine and Aiguebelle, the former for the treatment

of galena and tetrahedrite of the Gelon valley, the latter for smelting of the Argentine galena (Chabrand, 1905). Argentine presumably dates from much earlier periods yet, judging from the name of the village already existing at that time.

The history of the Molliet, Perrière and Chevrette mines is concurrent to that of the Carthusians of St. Hugon, the mines being their property. The sphalerite deposit situated upstream of their furnaces is not mentioned to have been exploited by them (Bouchayer, 1927). Probably they were not interested in mining other than iron.

The second part of the eighteenth century has been the most prosperous period for the region, all deposits known to day, having been worked then. Mining occurred for iron, lead, silver and copper. St. Georges alone yielded an annual copper production of 200 tons (de Saussure, 1779), which represented a large figure at that time. Several furnaces have been constructed for the treatment of galena. Between 1778 and 1790, however, the greater part of the smaller deposits (Riveret, Fosse Guerre, La Richesse, St. Hubert, Malrocher, Prodin and Remoud) have been shut down (Lelivec, 1806). The mines of Argentine and St. Georges des Hurtières were the sole to remain productive throughout the early part of the nineteenth century.

A revival of mining occurred in 1861 when in Randens and Argentine new blast-furnaces were built. A few smaller deposits were re-opened, special attention being given to Prodin, Remoud and Bonvillard.

In 1878 all mining rights were acquired by the Schneider-Creusot Company, who did not accept any more small privately won ore quantities, for their furnaces, but was mainly concerned with the St. Georges and Montgilbert deposits. These were developed to an annual production of 75.000 tonnes of ore (Chabrand, 1900). The Perrelle deposit has been exploited in 1900 on a merely tentative base (Bordeaux, 1925). The history of the St. Georges deposits runs parallel to that of Allevard's Taillat deposits. They too, were shut down in the end of the twenties.

The only recent mining activity took place in the Bonvillard region, where after two centuries of incidental surface excavations, mining started in 1920 on an industrial scale.

However, the exploitation never outgrew the exploratory stage, until they were closed in 1939.

Deposits not enumerated in this review are of such small size that they seemed unworthy of mention to Lelivec (1806) and Bordeaux (1925).

3 The mining methods and exploitation data

The sole deposit that has been operated continuously is the St. Georges siderite vein. Its notification in the thirteenth century shows the early interest. The actual start of the exploitation certainly is older (Hollande, 1911). The large scale of exploitation attained in the eighteenth century is evident from the description of the Saussure (1779), who mentions the number of 400 miners. At that time the deposits were the private property of many families, each exploiting their parcel and selling their products to the blast-furnaces of Randens and

Argentine.

No systematic mining occurred, the ores being won by open cast excavations or small inclined adits. Even the (10-12 meter) broad parts of the vein have not been timbered, although caving-in was common. Lelivec (1803) mentions the almost unbelievably dangerous conditions under which the miners worked when the glory hole reached depths of hundred meters or more. The annual production at that time reached 2600 ton.

Exploitation on a industrial scale occurred in the second part of the nineteenth century when the mines were acquired by the Creusot Company.

Its development appeared to be rather simple since the veins come close to the surface and only short adits were necessary. When exploitation ceased the greater part had been mined. The depth ultimately reached by the mining works amounts to 500 meters below the outcrops of the vein (1300 m). Exploratory work has shown the vein to continue some two hundred meters yet below the 800 m level, but the amount of quartz increases.

In the period from 1865-1885 the annual production attained 75.000 tons of iron ore of 38-40% iron. The pig iron produced by the blast furnaces contained about 15% manganese and was used for the fabrication of steel. Surface transport occurred by two inclined rope-hauled tracks from 1300 m to 915 m, a horizontal railway of 1300 m and three inclined tracks from 915 m to 330 m. These works still exist as do the ruins of the blast furnaces at the foot of the mountain on the left bank of the river Arc. Although partly caved-in, the Grande Fosse (915 m) trench is still of impressive dimensions. The most recent exploitation of St. Georges dates from the first world war.

The other important siderite vein, that of Chevrette, has only been developed by surface excavations, the mine being situated in an almost flat terrain close to the Veyton river. Molliet (geologically and mineralogically situated in the Allevard region) has been worked by the Carthusians (Hollande, 1911). The deposit comprises two intersecting veins of a half to two meters width. These have been developed by two adits from its northern side.

Other veins that were opened up for the production of siderite are those of Prodin (two crosscuts), Fruithiers (two crosscuts and three drifts) and Richesse.

The intersecting veins of the latter were attacked by numerous short, inclined adits and crosscuts, a chaotic assemblage of underground works being the result.

Argentine and Richesse have been operated for the production of silver. Both deposits are among the few ones where recrystallization of any extent has not been observed, and where the galena still retains bismuth and silver originally present.

The Malrocher, Prévieux, Perrelle and Bonvillard deposits have been subjected to recrystallization upon which the silver bearing galena and tetrahedrite were so intricately intermingled with barren material as to cause difficulties in ore dressing.

The exploitation object of the Bonvillard deposits was galena. Mining in the eighteenth and nineteenth century did not surpass the stage of surface excavations. The modern development, occurring in the twenties of this century, also failed to bring the deposits into production, only exploratory drift-adits having been made. The veins opened up in this way have been

shown to possess ore reserves of 30,000 ton of 7.6% galena and 2.4% sphalerite according to an unpublished report.

4 Geological outlines

A description of the geological formations met within the Aiguebelle region would be very similar to that of Allevard and therefore need not to be repeated here. Both regions are part of Outer Zone. The formations occurring comprise: the Outer Zone schists, Upper Carboniferous, Triassic and Lias. Permian is absent.

The sole aspect by which the Outer Zone schists differ from those of Allevard is their degree of retrograde metamorphism, biotite being more common. This feature bears relation to the tectonic deformation that gradually diminishes in the Belledonne's northern part. This feature will be mentioned in the next section.

5 Structural geology

a. The Median Syncline

The two main structural features: the Median Syncline and the Upper Carboniferous syncline, both delimiting the Aiguebelle region, have been dealt with in the other Belledonne ore districts. The Median Syncline's thrust fault has equal strike (N 40° E) and dip (30-40° to SE).

The Inner Zone has been upthrust over the Outer Zone, the amount of throw, however, gradually diminishes in northerly direction. In the northernmost part, the Grand Mont and Beaufortin districts, the Triassic covers in the Inner Zone are situated at almost the same altitudes as those in the Outer Zone (a mere difference of a few hundreds of meters, Bordet, 1957).

Apparently the compressive forces causing the overthrust have also diminished in this direction. Moreover the northern part of the Median Syncline has retained a great deal of its sedimentary content. According to Bordet (1957) the original difference in metamorphic grade also decreases towards the north.

The position of the Median Syncline in the Beaufortin region is disputed, because of bifurcation and parallel occurrences of other tightly compressed "synclines" similar to the Median Syncline. Claude Bordet even locates the Beaufort granite in the Outer Zone.

b. The Upper Carboniferous syncline of Grand Collet and Prodin

The southern part of the Aiguebelle region has been uplifted as compared with the Allevard region. This appears from the Grand Collet section, fig. 80. Possibly, this uplift has not occurred along the Carboniferous syncline alone, but may have been effectuated by several parallel faults. In this sense Dondey (1960) explains the deviations in dip displayed by the Permian cover of the Grand Collet.

This uplift has been invoked by the present author to explain the incompatibility that exists between the ore types of

Allevard and Aiguebelle regions and the actual level at which the ores now occur, the present differences in level being contrary to the theoretically ideal situation. The mesothermal Aiguebelle ores namely occur at higher altitudes than the epithermal Allevard ores.

North of Bourget the Upper Carboniferous syncline disappears under the allochthonous Mesozoic.

c. The décollement of the "Collines Liasiques"

The décollement of Jurassic and Triassic sediments, a feature so common in the southern ore districts, gradually loses significance in a northerly direction. The distance over which sliding took place is smaller for the Gelon area than for the Brame Farine of Allevard, and becomes very small near Bonvillard, where the folded Mesozoic masses still occur on the western flank of the Grande Arc.

North of the Isère river the sliding amounts to so little that the Liassic formations bordering the Belledonne's crystalline core, should be designated as a par-autochthonous cover.

d. The autochthonous cover and wrench fault system

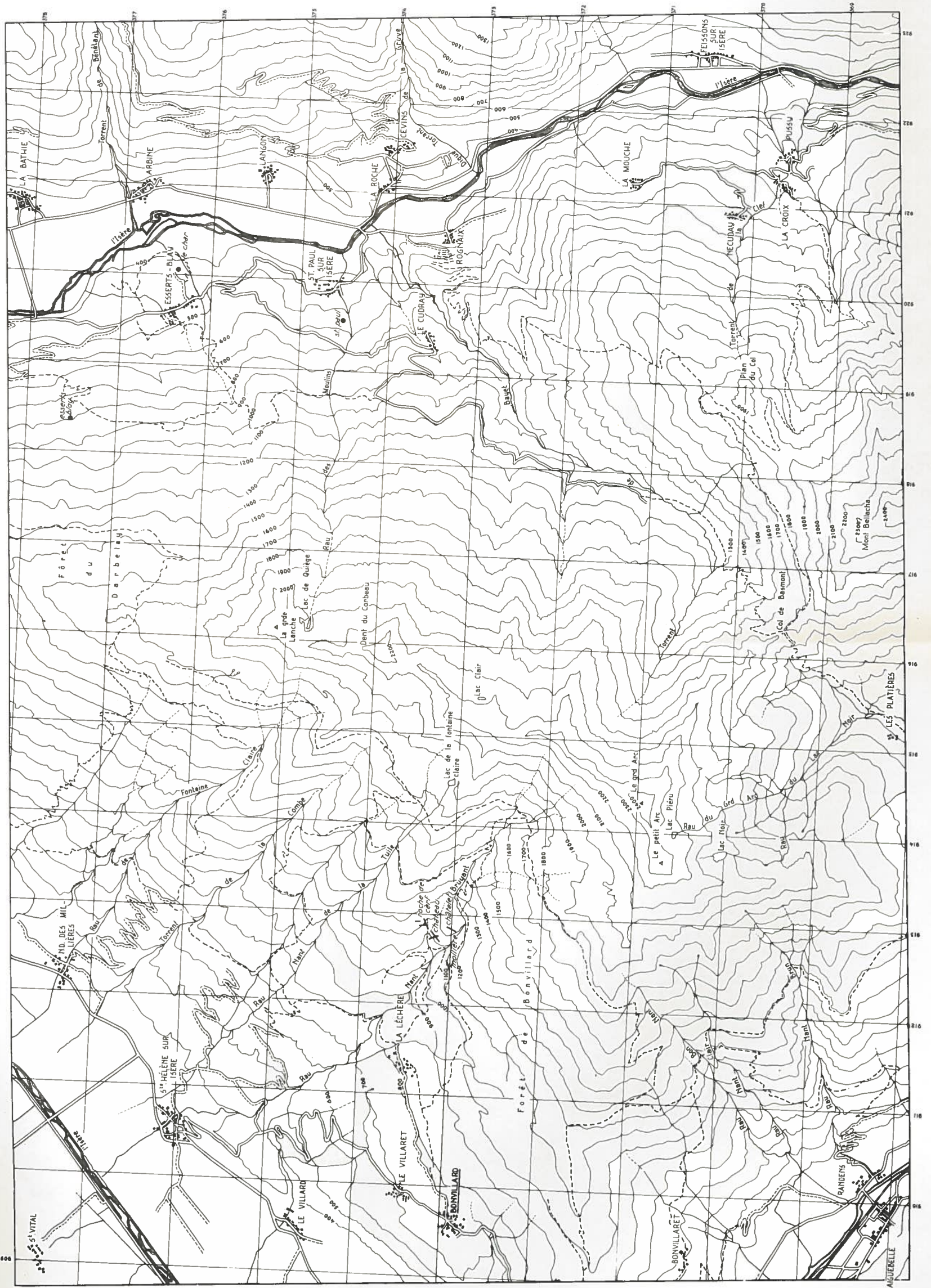
North of the Isère river the autochthonous sedimentary cover, so useful in reconstructing the Triassic peneplain, is commonly present at rather uniform altitudes, which means that the tectonic blocks ("claveaux" of Bordet, 1957) have been displaced by only small vertical movements. Thus, tracing the courses of possible faults is rendered still more difficult than in the Allevard region. Moreover, the effects of the broad valleys of Isère and Arc are morphologically so predominant that a possibly existing wrench fault system may completely have been covered up by alluvial deposits, an idea which is in agreement with the situation in the Allemont region where the Eau d'Olle and Romanche rivers are concurrent to the local directions of the wrench faults (Kalsbeek, 1962, Sarrot-Reynauld, 1961).

6 Shape and structural features of the ore deposits

In contrast with the ore deposits of the Allevard region, the shape of most Aiguebelle deposits is rather difficult to define. The veins are of lenticular shape, have repeatedly been pinched off, or show boudinage, identical to the structures mentioned in the Vizille region occurring east of the Upper Carboniferous syncline of Mont Jean.

The distribution of the ore minerals within the vein is even more arbitrary, since quartz being predominant over all other minerals has dissected the previously deposited vein content into numerous small streaky parts. Thus, the actual width of the ore shoot rarely exceeds 30 cms., although the total vein width may amount to 2 meters. The length of these strangulated veins does not exceed a hundred meters.

Exploitation of such veins involves a great deal of risk. The sole exception to this rule are the broad siderite veins of Chevrette, Molliet and St. Georges des Hurtières. The former has a width varying from 3.5 to 5 meters and has been excavated over



a length of more than hundred meters. The total length along the pitch may be considerably more, since the exploitation only touches part of the vein. The St. Georges vein is still more impressive and may attain, in its southern part, a total width of 10 meters, generally varying between 2 and 8 meters.

Its strike is about NW-SE. The vein is cut obliquely by ENE trending faults and resembles in this aspect the Taillat vein. The dip, however, is less being 20° to 60° to SW. Most veins in this region have more gentle dips than those of Allevard, varying between 35° (Molliet, Malrocher) 50° (Perrelle, Argentine, St. Hubert) and 80° (Prodin, Remoud, Fosse Guerre).

The diagram (fig. 87) representing strike-directions of the veins suggests, that the vein directions form part of a feather joint system belonging to transcurrent faults, just as in the Allevard region. Because of the monotony of the Outer Zone schists and the absence of autochthonous sedimentary coverings, it is almost impossible to trace the course of these faults.

If the vein trends are moulded upon a joint pattern feathering out from the wrench faults, the directions of the latter coincide with the NS to NNW-SSE trending valleys of Arc and Isère rivers and the ENE-WSW trending valleys of the Gelon, Ruisseau de Lac Noir and the Doron river, and those parts of the Arc and Isère rivers where these turn west before leaving the Belledonne. The NW-SE directed smaller streams and brooks, parallel to similar ones of the Allevard region, which perpendicularly dissect the Belledonne ridge, here too, likely correspond to the direction of maximum compressive stress.

7 Mineralogy

The paragenetic relations of the mineralization in the Aiguebelle region are not as easy to recognize as was the case with the ore deposits of the Allevard region, where two ore suites occur. As a whole the Aiguebelle region features the presence of only one suite comparable to the older one of Allevard. Frequent recrystallization has obliterated the original mineralogical or chemical qualities. An other process by which chemical alteration occurred is the injection of later quartz phases, dissecting the sulphide body into small streaks (fig. 88). The embedding by quartz caused an exsolution of material formerly kept in solid solution in the sulphides. This depleted the deposit of its chemical characteristics.

Moreover, the younger and older vein quartz can be discerned only with difficulty because of the content of their fluid inclusions. Both contain substantial amounts of gas, the older vein quartz more than has been observed in the Allevard region, since the (old) quartz of St. Georges displays a liquid homogenization of the CO₂-phase.

Thus, the high CO₂-content normally present in the younger quartz also appears to occur in inclusions of the older paragenesis. The younger vein quartz, on the other hand, generally occurs in deposits close to the Triassic peneplain, i.e. in a setting where low CO₂-densities prevail. Therefore it is sometimes impossible to tell whether the recrystallization of sulphides should be attributed to the older quartz or whether it should be interpreted as a phenomenon accompanying the younger

one. Moreover, there are indications that the younger quartz phase has induced secondary inclusions in formerly deposited quartz, eventually effecting a recrystallization of the latter.

The absence of stress effects, a criterium commonly used to distinguish the younger quartz, may fail to be a mark either, since the actual quantities of the strain free quartz are less than the presence of secondary inclusions, normally attributed to the younger quartz; make us believe there are. The final decision on the question whether we are dealing with syngenetic inclusions belonging to the older suite or secondarily induced inclusions of later origin has been made on the basis of the range of homogenization temperatures, being short with the older quartz, but large with the younger, irrespective of their CO₂ content. Another point on which the decision can be made is the relation between the degree of deformation and the type of inclusion that is present. Large CO₂-rich inclusions in a highly strained or cataclastic quartz are suspect, and are probably of secondary origin.

Whereas the strained quartz normally has lost its larger inclusions, these may still be present in quartz crystals of the same phase which are embedded in carbonates.

Carbonates are more apt to yield upon stress by plastic deformation than quartz, thus preserving the included quartz for strong cataclasis. The fluid inclusions in quartz I of St. Georges are to be looked at in this way.

Notwithstanding the distracting features just mentioned, the Aiguebelle area as a whole is of a rather typical mineralization. Sphalerite, tetrahedrite and galena are of wide spread occurrence and in places even exceed siderite in quantity. Few deposits, however, still show the original chemistry of the sulphides. Sphalerite, for instance, only has preserved its iron content when there happened to be no other vein constituents than sulphides or barite and when younger mineralization phases are absent. The sphalerites of St. Hugon, Fond de France and Esserts-Blay have FeS contents of 10-12.5 mol. % corresponding to a mesothermal genesis. These sphalerites only contain a few small exsolution drops of chalcocopyrite, which is less than the copper analyses indicate. The CuS-content, if calculated as CuFeS₂, corresponds to a chalcocopyrite percentage of 1.0 to 0.5 wt. %, quantities that certainly should be observable if present in individual minerals. Apparently this copper occurs as solid solution in the sphalerite lattice. Sphalerite from other deposits (Bonvillard, Perrelle, Malrocher, Fosse Guerre) that have recrystallized while embedded in quartz, siderite or ankerite have lost half of their iron content (4-6 mol. % FeS has been left), but show copper contents that are of the same order as those of Esserts-Blay and St. Hugon, containing 1.0 to 0.5 wt. % CuFeS₂. Apparently, the bulk composition has not changed, the exsolved chalcocopyrite still occurring in the sample as interstitial masses, or clusters bordering the sphalerites.

Galena behaves in a similar way as sphalerite. Few galena deposits have retained the original Bi-content, only those veins (Richesse, St. Hugon and Montgilbert) where later phases were insignificant or absent, display Bi-contents from 0.19 to 0.07%. All others are substantially lower and vary between 0.02 and 0.03%. Intermediate values do not occur. Like copper in sphalerite, the silver content is not so sensitive to



Fig. 88. Galena (high reflect.) and sphalerite (black) have been disrupted and dissected by quartz (white) into streaky fragments. Fosse Guerre, 1x.

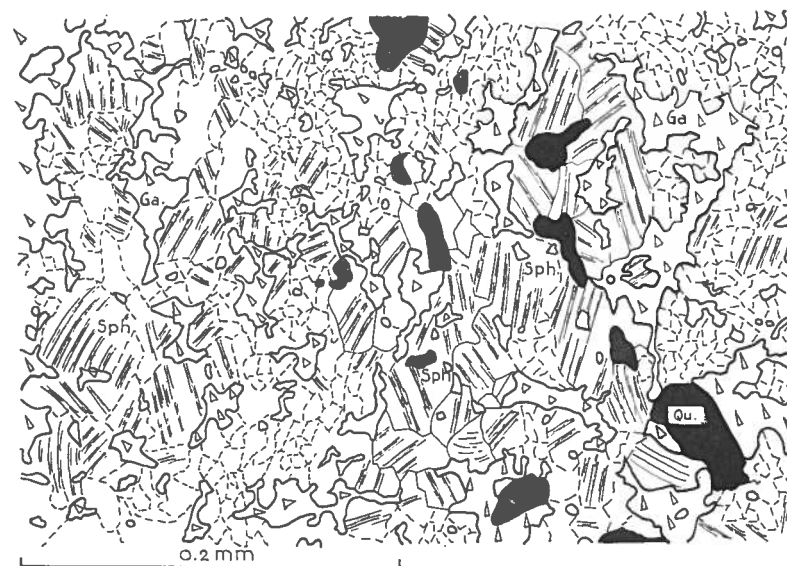


Fig. 89. Medium grained recrystallization fabric of galena (Ga) and sphalerite (Sph). Malrocher.

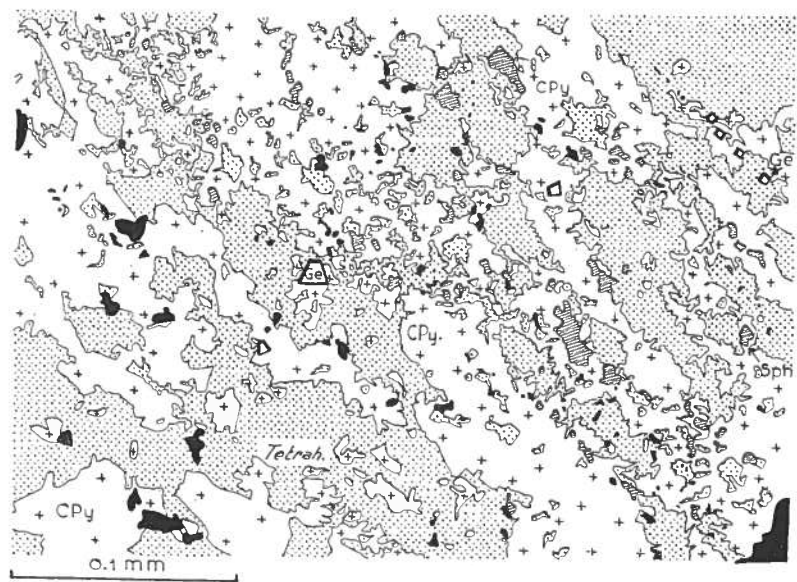


Fig. 90. Intricate intergrowths of tetrahedrite (tetrah.), chalcopyrite (Cpy) and sphalerite (shaded). Fine grained recrystallization fabric grown after strong deformation (roll-ore). Note trains of euhedral gersdorffite crystals (Ge). Remoud.



Fig. 91. Highly deformed barite-sulphide vein of Bonvillard (barite is white, sulphides are grey or reflecting spots), 2 x.

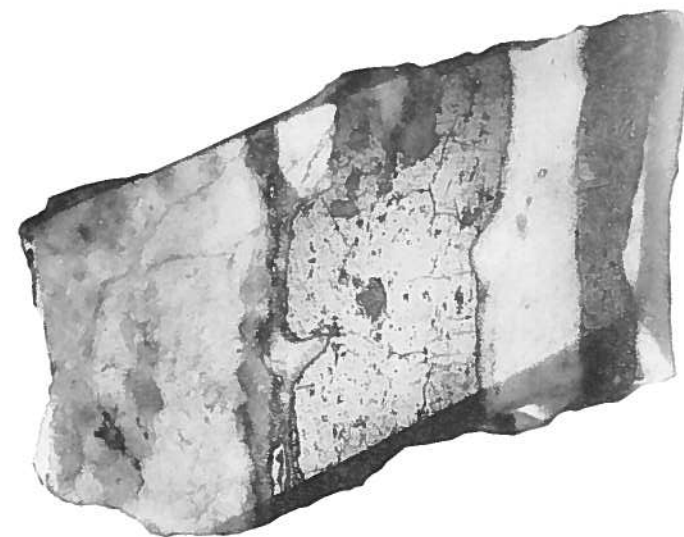


Fig. 92. Stretched sphalerite (reflect.) vein embedded in barite (white). Bonvillard, 2 x.

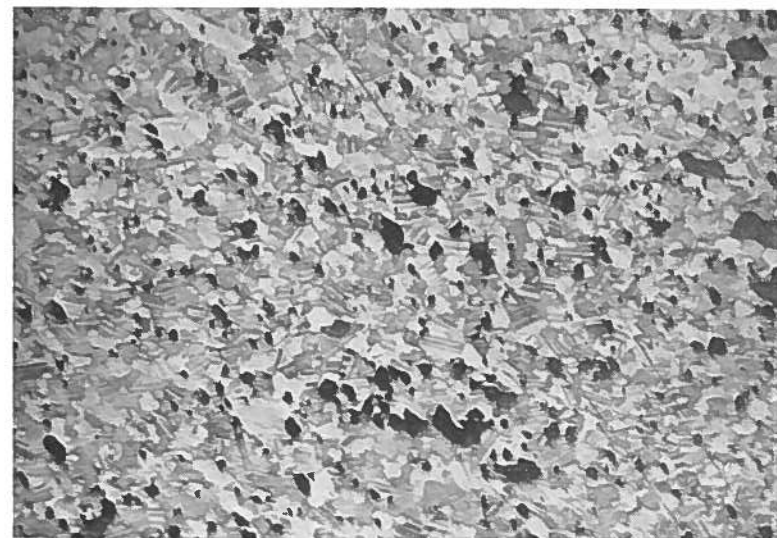


Fig. 93. Fine-grained recrystallization fabric of sphalerite of Bonvillard, detail of figure 92, etched by HI, 150 x.

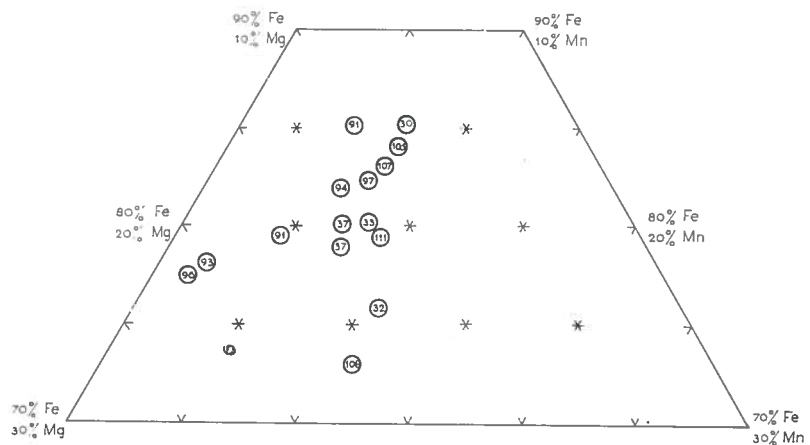


Fig. 94. Diagram representing the chemical compositions of siderites of the Allemont and Aiguebelle regions.

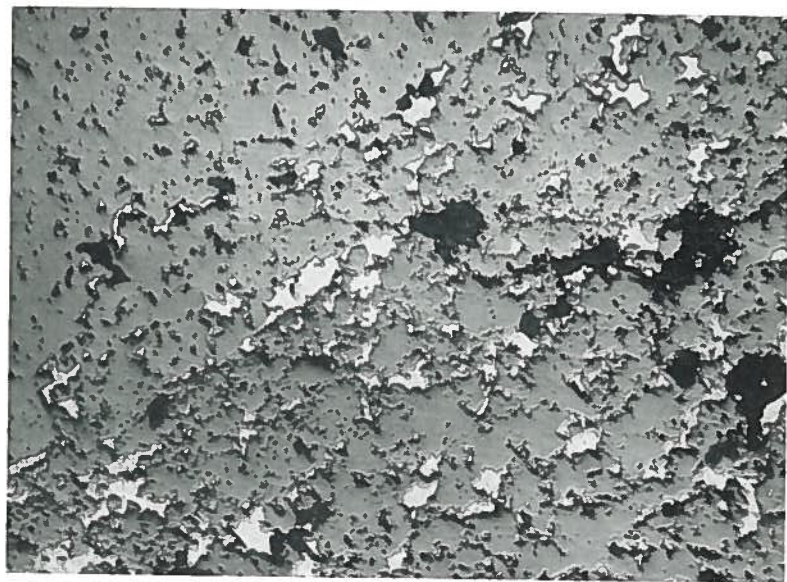


Fig. 95. Intergrowths of sphalerite (gray) and galena (white). Where sphalerite occurs in excess over galena, recrystallization is rare. Malrocher, 200 x.

recrystallization. The bulk percentages have been left almost unchanged (between 0.08 and 0.14 % Ag).

As a rule galena is much more susceptible to recrystallization than sphalerite. Whereas sphalerite shows distorted twin-lamellae of the larger crystals embedded in a finely ground matrix of hardly discernable grains (even at 250 x magnification), galena occurring in the same vein may form an isotropic fabric of coarse, equidimensional grains.

The effects of mechanical disruption and subsequent recrystallization present the most conspicuous feature displayed by the Aiguebelle ores. Micro-crystalline aggregates of intricately intergrown sphalerite, galena and tetrahedrite are common in the St. Hugon, Remoud, Prodin and Malrocher deposits. The individual minerals occur in vague streaky portions parallel to the wall. At high magnification it appears that recrystallization affected all minerals together in such an intricate manner as if the three main minerals have formed part of a solid solution system that simultaneously with the exsolution process has been rolled out (fig. 90 and 95). The fabric produced in this way closely resembles the metamorphic ores of Rammelsberg as described by Ramdohr (1953).

Where galena forms the main vein constituent the rolling features are less conspicuous and may even have been wholly obliterated by the progress of recrystallization to a coarse fabric resulting in granoblastic intergrowths of sphalerite and galena (fig. 89, Prévieux, Fosse Guerre, Perrelle, les Mouches). Also in veins where siderite occurs in excess over the sulphides recrystallization may have led to a new fabric, the carbonates being more easy to be restored (St. Georges, La Chevrette, Bonvillard). Actually siderite does not occur in the sulphide veins of Remoud and Prodin.

Concerning the Bonvillard deposits it is interesting to note that recrystallization of sulphide is complete when occurring within siderite whereas the sulphides embedded in barite hardly have been recrystallized. Figure 91 even shows folded masses of sulphides, barite, ankerite and quartz. Ankerite and quartz constitute nodules in a finely ground crystal mass. Figure 92 shows the picture of a finely recrystallized sphalerite of equigranular fabric occurring as streaks in barite. Figure 93 shows the recrystallization fabric, and represents a detail of fig. 92.

Siderite occurs in two types but prevails in the older paragenesis. With the latter its manganese content is remarkably high, specially with the fine grained, almost mylonitic siderite: St. Georges (Fe/Mn ratio: 6.9), Bonvillard (Fe/Mn ratio: 6.4) and Montgilbert (Fe/Mn ratio: 6.6). The coarser grained siderite, occurring in the same deposit, has a slightly lower Mn-content (Fe/Mn ratio: 10.2) and apparently has recrystallized. The chemical composition is diagrammatically represented by fig. 94. This loss of manganese, however, is insignificant as compared to the Mn-content of the few siderite deposits that belong to the younger mineralization suite and feature Fe/Mn ratio's of 40-50. These siderites (and affiliated ankerites) are comparable to siderites of the Allevard region.

Summarizing we may conclude that:

- some strongly deformed deposits have still retained their original chemistry.

- recrystallization is common and resulted in a loss of certain trace elements and a restoration of the fabric.
- carbonates and mineralization by a younger ore suite, comparable to that of Allevard, are rare.

8 References

Lelivec's (1803 and 1806) and Verneihl's (1807) statistical reports on the mines and ore deposits of the Savoy department presents the same source of information for the Aiguebelle area as did Gueymard's study for the ore districts of the Isère department. Lelivec's works are of great value for establishing the history and situation of the ore deposits, as they were written at a time that the ore exploitations were still in progress. A drawback of these old publications, however, is the feature that many of the locality names mentioned are no more in use to day. Later studies of Grillet (1807) and Barbier (1878) do not add new data. In more recent times the mineral wealth of Savoy has been the subject of study to many authors: Borel (1889), Hollande (1911), Revil (1916), Moret (1925), Bordeaux (1925). The reviews of Hollande, Moret and Bordeaux are quite extensive and have been of great help in locating the ore deposits, but they are sparing with mineralogical and chemical data.

Historical information on the region comes from Brunier (1853), Gaillard (1924), Carcel (1936) and Blanchard (1941).

SUMMARY AND CONCLUSIONS

The results of this paper comprise an evaluation of data provided by fluid inclusions, a contribution to the mineralogy and chemistry of the ore deposits of the Belledonne Range and a concept of the process of rejuvenation of ore deposits.

Evaluation of the liquid inclusion data

Liquid inclusions may yield most valuable information about the physical conditions of crystallization of their host. The application of liquid inclusions as geological barometers and thermometers was hitherto confined to inclusions containing water as sole volatile constituent (Ingerson, 1947; Kalyuzhnyi, 1955) eventually corrected for estimated or analyzed dissolved solids (Lemlein, 1961; Lisitsin, 1961; Maslova, 1961). The presence of a second volatile phase was regarded to render the inclusions of little value for geological thermometry (Correns, 1953; Yermakov, 1957). However, a second volatile phase other than water, has been ascertained for most quartz crystals of the Belledonne's ore mineralization. The volatile phase has been identified as carbon dioxide by its chemical properties and the critical phenomena displayed at 31°C. At or below this temperature many inclusions become three-phase, a state that may be reached in two ways: either the CO₂-rich phase shrinks to form a gaseous CO₂ phase, or the CO₂-rich phase condenses to form liquid CO₂.

Not all CO₂-containing inclusions could be transformed into the three-phase state by cooling below 31°C, although the presence of CO₂ had been demonstrated by the crushing test. Deicha (1955) referred to the vapour phase of such non-condensable gas-containing inclusions, as a "spherical body" instead of a true "void of shrinkage". Inclusions of the "spherical body"-type are so common that fluid inclusion thermometry, if restricted to water-salts systems only, should find little application.

However, a theoretical evaluation of the system CO₂-H₂O, based on the relative data provided by the inclusions, and on the absolute values of Kennedy (1950, 1954), Khitarov (1956, 1958) and Malinin (1959) have developed this system also to such extent that it can be used in geothermometry:

- The three-phase state of an inclusion means that the pressure-temperature relations in the 0°-31° range are precisely known, irrespective of the relative quantities of CO₂ and H₂O, the system being univariant.
- In this temperature range the density of the CO₂-rich phase can be determined, if temperature and mode of homogenization of the CO₂-rich phase are known, making use of Kennedy's tables.
- The position of the three-phase line indicates that even in the case of low CO₂-densities the pressure within the inclusions is sufficiently high to dissolve detectable quantities of CO₂ in the water-rich phase. This explains the gas-content of the "spherical body"-type inclusions, and its inability to produce a liquid CO₂ phase on cooling, since at lower temperatures still more CO₂ can be solved in water, and

in this way the three-phase line is not intersected by the inclusion's isochore in the 0°-31° range.

- A cooling device is therefore of similar interest as the heating stage.
- The density of the CO₂-rich phase serves to distinguish between supra- and infra-critical gaseous homogenization (fluid homogenization by an increasing gas phase). A high CO₂-density points to supra-critical, low CO₂-density may result into infra-critical homogenization.
- The course of the isochore is determined in its lower temperature reach (0°-200°) by the density of the CO₂-rich phase, in its high temperature reach (200°-350°) by the filling degree with water.
- Isochores, boundary curves, and critical curves as constructed in fig. 28, 32, 33 and 13, denote the process of homogenization.
- The three-dimensional PTV-diagrams (fig. 26 and 27) allow the interpretation of critical phenomena, and the determination of critical CO₂ : H₂O ratios, in the same way as has commonly been done for the PTV relations of water (fig. 1).
- Decrepitation occurs at temperature values that correspond with the steep part of the course of the isochore, and thus will take place earlier with inclusions of high CO₂ densities, than with water-filled inclusions under otherwise equal conditions.
- Crystallization at temperatures and pressures at which the mother liquid's isochore intersects the CO₂-H₂O boundary surface may enhance the possibility of heterogeneous entrapment. Actually, entrapment of heterogeneous fluids is not rare at all (Little, 1955; Kalyuzhnyi, 1960).
- Finally, the possibility of extrapolating the courses of the isochores means that the application of CO₂-containing inclusions to geologic thermometry is made possible.

Contribution to the mineralogy

Some rare minerals have been identified in the ore deposits of the Belledonne. They comprise: argentopyrite (from Chalanches), boulangerite (widespread), coronadite (fifth occurrence in the world), polybasite (Chalanches) and gersdorffite-ullmannite (widespread). The Bi-content of galena, the Fe-content of sphalerite and the Mn-contents of siderite and ankerite appeared to be of great geochemical value. The relation between the chemical composition of ankerite and its lattice spacings has been investigated.

The process of rejuvenation of ore deposits

Two types of ore deposits have been discerned: an older and a younger one. The older is characterized by:

- Mesothermal paragenesis, high Fe-content of sphalerite, high Bi- and Ag-content of galena, and manganiferous siderite. Ni-Co-minerals are common.
- Strained appearance, intricately intergrown crystals, anisotropic fabric.
- Sequence of sulphides followed by siderite.

- Quartz inclusions of high filling degree but low CO₂ content, homogeneous entrapment. Pressure corrections have to be applied for establishing crystallization temperatures.

The younger mineralization is to be recognized by:

- Epithermal paragenesis, low trace-element content of the sulphides, magnesian siderite, small quantities of sulphides.
- Isotropic fabric.
- Sequence of siderite followed by sulphides.
- Quartz inclusions of lower filling degrees but higher CO₂-content, frequent heterogeneous entrapment. Homogenization temperatures equal crystallization temperatures.

There are several reasons why to interpret the young mineralization as a product of rejuvenation of the older one.

MINERALOGICAL EVIDENCE FOR REJUVENATION

Although of an impoverished chemistry the mineralogy of both suites is much alike, the same minerals occur, but the relative quantities have changed. Minerals of the older suite, which have a marked tendency to recrystallization, have become more abundant in the younger suite. The proportions of galena and sphalerite are reversed in younger formation. The relative quantities of sulphides have also changed. Siderite is particularly abundant in the younger type, a feature also known from other rejuvenated deposits (Huttenlocher, 1953).

CHEMICAL EVIDENCE

Between the siderites of both formations a large compositional gap exists. Intermediate compositions only have been noted from veins where both mineralizations occur, apparently representing an initial stage of rejuvenation. The factor by which the Mn-content has decreased is constant over the whole of the Belledonne, which resulted into a fixed ratio between both siderite-types from one area. The difference in trace-element content of the sulphides is too large and too constant to be attributed to a mere recrystallization.

TEXTURAL EVIDENCE

All minerals of the older suite display stress effects, such in contrast to the younger suite.

PHYSICAL EVIDENCE

All isotopic ratios of lead point to Upper Carboniferous to Permian age, even with those lead deposits that are emplaced during the Alpine orogeny. The most remarkable proof of rejuvenation of ore deposits has come from the investigation of liquid inclusions. Where both types of quartz occur in the same vein or are closely spaced, it has been shown that entrapment of both mineralizing solutions took place under different geological conditions. The younger type has been deposited at shallower depth than the older one. The younger quartz crystallized at such depth that at 200 meters from the Triassic peneplain the density of the mother liquid was just critical with regard to the kind of phase transformation of the CO₂-rich phase in the 20°-31° range. The fluid inclusions, the homogenization temperatures and the mineralogy of the younger paragenesis indicate an ore-free hydrothermal solution as rejuvenating agent, and thus confirm the idea of Schneiderhöhn (1952), that "Erzleere Thermen" might have brought on the rejuvenation. The mesothermal character of the rejuvenated vein as defined by the physical point of view sharply contrasts with its epithermal mineral content.

STRUCTURAL AND GEOLOGICAL EVIDENCE

The age difference between both ore suites is a strong argument for rejuvenation. Correlation by means of the chemistry of siderite and fluid inclusions has shown that the Alpine age of some deposits occurring in Mesozoic sediments can be inferred for many others. The presence of friable inclusions of vein quartz belonging to the ore mineralization on an Alpine thrust plane points to a late Alpine age. Another age indication comes from the control of deposition by the distance to the Triassic peneplain, which has been noted all over the Belledonne. The age of the older paragenesis is not so clearly to demonstrate.

There are, however, indications that we are dealing with Hercynian deposits.

- A pre-Triassic age has been proved by means of liquid inclusions.
- The "model age" is Upper Carboniferous to Permian (Kulp, 1960).
- The older ore deposits occur within a certain distance from the Upper Carboniferous covers. In areas, where these covers are not met, ore deposits, actually, do not occur.
- The calcite-ankerite veins accompanying retrograde metamorphism of probably late Hercynian age are intermingled with ore solutions of the older paragenesis.
- The older deposits have been subjected to regional metamorphism (stilpnomelane).
- A genetical relation between the central granite (Epière - Sept-Laux) and the ore deposits should be admitted, since close to the granite catathermal deposits occur (Argentine; St. Hugon; Fond de France). This zone is followed by mesothermal Pb-Zn deposits accompanied by highly manganese-rich siderite, whereas further away the manganese-content of siderite diminishes (Vizille area) and lead zinc deposits become subordinate. Where the central granite has been deeply eroded and no relics of Upper Carboniferous and Triassic occur, ore deposits are absent. This feature constitutes reason why the Belledonne is so richly endowed with ore deposits and departs in this respect from other Hercynian external massifs where large granite outcrops predominate (Aar, Mont Blanc).

The strike of both younger and older veins are moulded upon a feather-joint system belonging to the wrench fault directions, that developed penecontemporaneously with the emplacement of the granite.

Alpine rejuvenation of these faults produced the same set of feather joints. This constitutes a most favorable condition, if not a requirement, to rejuvenation of ore deposits.

Finally, whereas the primary ore deposits are distributed over the Belledonne within a certain distance from the granites irrespective of pre-Hercynian geology, the rejuvenated ones are confined to lenticular tectonic blocks (the "clavaux" of Bordet, 1957), which still possess Permian and Triassic covers.

Apparently, the rejuvenating solutions have not been generated by post-kinematic, high level acid igneous rocks, but by some deep-seated differentiation process, products of which moved upward along major tectonic scars.

RÉSUMÉ

Les résultats de ces recherches comprennent:

- une interprétation génétique des inclusions fluides contenant du CO₂.
- une contribution à la géochimie et à la minéralogie de la province metallogénique de la Belledonne.
- une étude du processus de régénération des gîtes métallifères

On a cru jusqu'à présent que les inclusions fluides contenant du CO₂ n'étaient pas propres à servir de thermomètre géologique (Yermakov, 1957). Ceci implique, au fond, que fort peu d'inclusions pourraient entrer en ligne de compte pour cette application, puisque Deicha (1955) a montré que de nombreuses inclusions réagissent par un dégagement de gaz à l'essai par écrasement, bien qu'une phase riche en CO₂ n'ait pu être démontrée au microscope par la condensation d'anhydride carbonique. Une transposition du système CO₂-H₂O sur le plan théorique, basée sur les transitions des phases dans les inclusions, et les données physiques de Kennedy (1950, 1954), de Khitarov et de Malinin (1956, 1958, 1959) ont permis d'utiliser également des inclusions, qui contiennent du CO₂ pour une thermométrie de la cristallization. Les résultats sont traduits par des diagrammes appelés isochores (fig. 28, 32 et 33), qui indiquent le changement de températures et de pression pour une certaine proportion de CO₂ : H₂O à volume constant. La direction des courbes isochores détermine si la phase riche en CO₂ s'homogénéisera en phase fluide ou en phase liquide à la température critique du CO₂ (31° C). L'extrapolation de ces isochores en dehors de la limite de deux phases permet l'application de corrections de pression pour une thermométrie absolue. La lecture des diagrammes tridimensionnels de température de pression, et de volume (fig. 26 et 29) permet de déduire la degré critique de remplissage pour une certaine composition.

L'examen des inclusions a démontré que les deux phases de minéralization, qu'on peut distinguer à base minéralogique et à base chimique, se sont développées à deux époques géologiques différentes. Il est permis de dater la minéralization plus anciennes comme Hercynienne pour les raisons suivantes:

- le rapport des isotopes de plomb accuse un âge Houiller ou Permien,
 - les gisements sont métamorphosés,
 - il y a une certaine disposition zonale par rapport au granite central Hercynien, allant des paragenèses cata-thermales à des paragenèses mésothermales,
 - Les minerais se sont déposés en diaclases d'extension appartenant à des failles transversales de décrochement d'origine Hercynienne, qui se sont développées à même temps que la consolidation du granite central.
- La jeune minéralization est sans doute d'âge alpin; la présence des minerais dans des formations Secondaires et dans des plans de failles alpines en fait preuve, ainsi que le fait que la position de la pénéplaine Triasique détermine la densité des inclusions riches en CO₂. La densité est moindre près de cette pénéplaine qu'à une certaine distance.
- Après avoir démontré que la minéralization de la Belledonne s'est accomplie en deux phases géologiques, il est remarquable de

constater que le contenu minéralogique de ces deux phases est indentique (quoique dans un ordre de cristallisation inverse), et qu'il existe un certain rapport entre les compositions chimiques des sidéroses les plus jeunes et les plus anciennes. La teneur en manganèse est diminuée de moitié à peu près, indépendamment de la teneur originale. Ces congruences s'expliquent par la régénération Alpine d'un gîte Hercynien. La différence, qui existe entre les vraies températures de cristallisation de la jeune minéralisation telles qu'elles sont indiquées par les températures de homogénéisation des inclusions ($300^{\circ} \pm 30^{\circ}$), et la température de cristallisation qui est généralement attribuée à la paragénèse épithermale, est une confirmation de l'idée de régénération.

SAMENVATTING

De resultaten van dit onderzoek omvatten:

- een genetische interpretatie van CO_2 -houdende vloeibare insluitels in mineralen,
- een bijdrage tot de geochemie en mineralogie van de Belledonne ertsprovincie,
- en een bestudering van het proces van regeneratie van erts.

Tot nu toe werden CO_2 -houdende insluitels in mineralen niet geschikt geacht om als geologische thermometer gebruikt te worden (Yermakov, 1957). Dit betekent, dat eigenlijk zeer weinig insluitels voor deze toepassing in aanmerking zouden mogen komen, daar Deicha (1955) er op heeft gewezen, dat vele insluitels positief reageren op de verbrijzelingsproef, hoewel een CO_2 -rijke fase microscopisch niet kon worden aangetoond door condensatie van vloeibaar CO_2 . Een theoretische behandeling van het systeem CO_2 - H_2O gebaseerd op fase-veranderingen in de insluitels en de fysische gegevens van Kennedy (1950, 1954), Khitarov en Malinin (1956, 1958, 1959), heeft het mogelijk gemaakt ook CO_2 -houdende insluitels voor kristallisatie-temperatuurbepalingen aan te wenden. De resultaten zijn vervat in diagrammen, die de verandering van temperatuur en druk voor een bepaalde verhouding CO_2 : H_2O bij gelijk volume aangeven, de zogenaamde isochoren (fig. 28, 32 en 33). Het verloop van de isochoren bepaalt of de CO_2 -rijke fase gasvormig, dan wel vloeibaar zal homogeniseren bij de kritische temperatuur van CO_2 (31°C). De extrapolatie van deze isochoren buiten het twee-fasen bereik maakt de toepassing van drukcorrecties voor absolute temperatuurbepalingen mogelijk. Uit de drie-dimensionale temperatuur-, druk- en volume-diagrammen (fig. 26 en 29) is de kritische vullingsgraad voor een bepaalde samenstelling af te leiden.

Het insluitelonderzoek heeft aangetoond, dat de twee verertsingsfasen, die mineralogisch en chemisch onderscheiden konden worden, hebben plaatsgevonden in twee geologisch verschillende perioden. Men veronderstelt, dat de oudste verertsing Hercynische ouderdom heeft om de volgende redenen:

- De lood-isotopen verhouding wijst op Boven Carbonische tot Permische ouderdom.
- De erts zijn metamorf beïnvloed.
- Er bestaat een zekere zonerings-ten opzichte van de Hercynische Centrale graniet, waarbij de paragenesen, naar gelang de afstand tot deze graniet variëren van kata- tot mesothermaal.
- De erts zijn afgezet in rek-diaklazen, behorende bij transversale breukbewegingen, die Hercynisch van oorsprong zijn en gelijktijdig met de stolling van de Centrale Graniet tot ontwikkeling kwamen.

De jonge verertsing is zonder twijfel van Alpiene ouderdom; erts-voorkomens in Mesozoïsche gesteenten en op Alpiene breukvlakken wijzen hierop, evenals het feit, dat de afstand tussen erts-afzetting en het niveau van de Trias de dichtheid van de CO_2 -rijke insluitels bepaalt. Dichtbij dit niveau is de dichtheid geringer, dan verder hiervan vandaan.

Na aangetoond te hebben, dat de verertsing van de Belledonne heeft plaatsgevonden in twee geologisch verschillende fasen, is het opmerkelijk te constateren, dat mineraalinhoud van beide gelijk is (zij het in omgekeerde kristallisatie volgorde) en dat

er een bepaalde verhouding bestaat tussen de chemische samenstellingen van de jongere en de oudere siderieten. Het mangaangehalte van de jonge siderieten is ongeveer gehalveerd t.o.v. die van de oude siderieten, onafhankelijk van het oorspronkelijke mangaangehalte. Deze congruentie wordt verklaard door Alpiene regeneratie van een oud Hercynisch erts. In overeenstemming hiermee is het verschil tussen de werkelijke kristallisatie temperaturen van de jonge vererzings, zoals deze blijkt uit de homogenisatie temperaturen van de insluitsels ($300^{\circ} \pm 30^{\circ}$), en de lage vormingstemperaturen, die gewoonlijk aan deze epithermale mineraal associaties worden toegeschreven.

ACKNOWLEDGEMENTS

The study of the ore deposits of the Allevard region started in 1953 as part of the petrological investigations of the Belledonne Range by Prof. Dr. E. Niggli (Bern), at that time chairman of the petrological department of the Leiden Geological and Mineralogical Institute. In 1955, when Prof. Dr. W.P. de Roever (Amsterdam) succeeded Prof. Niggli the investigations of the ore deposits were extended by the author to the whole Belledonne, whereby much help was offered by Prof. Dr. L. Moret and his staff of the Grenoble Geological Institute. The permission given by Mr. Moret to make free use of the maps of the archives of the "Société des Hauts-Fourneaux et des Forges d'Allevard" was of great value for locating the ore deposits of the Allevard region. The author owes many informations about ore occurrences to the petrological studies on the Belledonne by the Leiden group, such as made by Mr. A.J.A. Janse, Mr. P. Maron, Mr. N.A.L. Touwen and Mr. R. v.d. Wart. Besides by them, samples have also been provided by Dr. P.C. Zwaan of the "Rijksmuseum voor Geologie en Mineralogie", Dr. C.O. van Regteren Altena and Mr. J.R. Möckel of the "Teylers Museum" at Haarlem and Mr. J. Lannes (Froges, Isère).

Mrs. Dr. C.M. de Sitter-Koomans (of the Leiden Petro-chemical laboratory) and Ir. J.C. Oudesluys (of the "Hollandse Metallurgische Industrie Billiton") aided in determining the procedures for the chemical analyses. The greater part (about 80 percent) of the analyses have been performed by Miss H.M.I. Bik, the other part by the author. An introduction to the techniques of fluid inclusion investigation the author owes to Dr. J.W. Brinck (Ispra). Dr. P. Hartman (Leiden) has given many suggestions about the chapter dealing with the thermodynamical treatment of the system $\text{CO}_2\text{-H}_2\text{O}$. The determination of the isotopic ratios of lead have been carried out by Dr. A.J.H. Boerboom and Dr. H.N.A. Priem of the F.O.M. Laboratory for Mass-separation.

An geological interpretation of the results derived from the ore studies would not have been possible without the discussions the author has had with his colleagues: Dr. F. Kalsbeek, Mr. H. Koning and Dr. A.C. Tobi and the present chairman of the Petrologic department Prof. Dr. E. Den Tex, who finally guided this graduation study.

The author is greatly indebted to Mr. J. Bult who has drawn the geological map and all the figures, to Mr. A. Verhoorn who prepared the X-ray diagrams, to Mr. M. Deyn and Mr. C.J. van Leeuwen who prepared the thin sections and polished specimen, to Mrs. M. Overeem-van Heel who prepared the french summary, and to Mrs. J.A. Mark-Ouwersloot, Mrs. M.J.J.H. van der Velden-Friebel, and Miss I.C.J.M. van Leeuwen, who typed the manuscript.

SELECTED REFERENCES ON THE MINERALOGY AND FLUID INCLUSIONS THERMOMETRY

- Allègre, C.I., 1961. "De l'application de la résonance paramagnétique nucléaire, à l'étude des inclusions fluides".
Compte Rendu Soc. Geol. France, p. 178.
- Angel, 1939. "Lehrfahrt auf den steterische Erzberg". Fortschr. Miner. bd. 23, p. 54-76.
- Bakhuis Roozeboom, H.W., 1904. "Die Heterogene Gleichgewichte, I". 1904.
- Bakhuis Roozeboom, H.W. & Büchner, E., 1918. "Die Heterogene Gleichgewichte, II", 1918.
- Bastin, E.S., 1950. "Interpretation of ore textures". Geol. Soc. of Amer. Memoire 45.
- Baumann, L., 1958. "Tektonik und Genesis der Erzlagerstätte von Freiberg (Zentralteil)". Freiburger Forschungshefte.
- Boulanger D. & Deicha G., 1960. "Rapports entre phase hydrothermale et pneumatolytique dans la formation des pegmatites".
Rep. 21th sess. intern. geol. Congr. Norden, part 17 p. 108.
- Brinck, J.W., 1955. "Goudafzettingen in Suriname". Leidse Geol. Meded. deel 21 p. 1-246.
- Byström, A. & Byström, A.M., 1950. "The Crystal Structure of Hollandite, and related Manganese Oxide Minerals. Acta Crystal. vol. 3, p. 146.
- Cameron, E.M., Rowe, R.B. & Weis, P.L., 1953. "Fluid inclusions in beryl and quartz from pegmatites of the Middletown district, Connecticut". Amer. Miner. vol. 38, p. 218-262.
- Caubet, F., 1902. "Verflüssigung von Gasgemengen, Chlormethyl und Schwefeldioxyde. Zeits. Phys. Chem. bd. 37, p. 639.
- Correns, W., 1953. "Wie weit können Flüssigkeitseinschlüsse mit Gasblasen in Kristallen als geologische Thermometer dienen?".
Geol. Rundschau, vol. 42 p. 19-34.
- Deer, W.A. et al. 1962. "Rock-forming minerals". 5 vol. London.
- Deicha, G., 1952. "Dispositif expérimental pour l'observation directe de la décrépitation des inclusions liquides d'origine hydrothermale".
Bull. Soc. France Miner. tome 75, p. 237-245.
- Deicha, G., 1955. "Les lacunes des cristaux et leurs inclusions fluides".
Masson, Paris, 126 p.
- 1960. "Distillations et condensations fractionnées de fluides géochimiques d'origine profonde". Bull. Soc. Geol. France (7), II p. 64.
- Doelter, C., 1911. "Handbuch der Mineralchemie". Dresden.
- Dunn, J.A., 1937. "Microscopic study of the Baldwin ores". Rec. Geol. Survey India, vol. 72, p. 333-357.
- Edwards, A.B., 1947. "Textures of the ore minerals and their significance". Melbourne.
- Elison, M. & Polykovskii, 1961. "Some characteristics of the process of the formation of quartz crystal pegmatites as revealed by an investigation of gas inclusions in minerals and rocks". Geochemistry no. 10, p. 977-987. translated of Geokhimiya 1961 no. 10.
- Ellenberger, F., 1957. "Le stilpnomelane, minéral de métamorphisme dans la Savoie (Savoie)".
Compte Rendu Soc. France, p. 63-65.
- Friedrich, O., 1933. "Die Erze und der Vererzungsvorgang der Kobalt-Nickel-Lagerstätte Zinkwand-Vöthtern in den Schladminger Tauern". Berg- u. Hüttenmänn. Jahrb. 81-1-14.
- Goldsmith, J.R. et al. 1962. "Studies in the system $\text{CaCO}_3 - \text{MgCO}_3 - \text{FeCO}_3$ ".
Journ. of Geology vol. 70, no. 6, p. 659-689.
- Golovanov, I.M., 1960. "Coronadite from the zone of oxidation of the lead-zinc deposits of Kurgashinkan (Uzbek, U.S.S.R.)".
Doklady Akad. Nauk S.S.R. vol. 130 no. 4, p. 843-845.
- Graf, D. & Goldsmith, J., 1958. "Relation between lattice constants and composition of the Ca-Mg carbonates". Amer. Miner. vol. 43, p. 84-101.
- Grigorev, 1948. "Problème de la distinction des inclusions liquides primaires et secondaires". Mineral. Sbornik. Geol. Soc. L'vov. no. 2, p. 75-81.
- Guillemin, C. & Levy, C., 1957. "Sur les minéraux du sondage de Petitchet (Isère)".
Bull. Soc. France Min. tome 80, p. 237-238.
- Haenel, O., 1920. "Löslichkeit Kohlensäure ins Wasser". Centralbl. Miner. und Geol. p. 25-30.
- Hallimond, A.F., 1939. "On the relation of chamosite and daphnite to the chlorite group". Min. Mag., vol. 25, p. 441.
- Hiller, J.E., 1938. "Röntgenographische Bestimmungsmethoden und Untersuchung der Bleispieszglasze". Zeits. Krist. bd. 100A, p. 128-156.
- Hutton, C.D., 1956. "Further data on the stilpnomelane mineral group".
Amer. Miner. vol. 41, p. 608.
- Ingerson, E., 1947. "Liquid inclusions in geologic thermometry".
Amer. Miner. 32, p. 375-388.
- Kalyuzhnyi, V.A., 1954. "Measurement of the index of refraction of free liquids and mother liquors included in minerals by using the Fedorov stage". Mineral. Sbornik Geol. Soc. L'vov. no. 8, p. 315-344.
- 1955. "Liquid inclusions in minerals as a geological barometer".
Mineral. Sbornik. Geol. Soc. L'vov., p. 64-85.
- 1956. "New observations on the phase-transitions in liquid inclusions".
Mineral. Sbornik. Geol. Soc. L'vov., p. 77-81.
- 1957. "Results on pH measurements in solutions from liquid inclusions".
Geochemistry, no. 1, p. 93-96, translated of Geokhimiya 1957, no. 1.
- 1958. "The study of the composition of minerals of poliphasal inclusions".
Mineral. Sbornik. Geol. Soc. L'vov., no. 12, p. 116-129.
- Kalyuzhnyi, V.A. & Shchirica, A.S., 1962. "Caractéristique physico-chimique des fluides $\text{H}_2\text{O} - \text{CO}_2$ ". Akad. Nauk. Ukr. S.S.R. Geol. Zh. tome 22, p. 29-41.
- Katz, D.L. & Kurata, F., 1940. "Retrograde condensation". Industr. Engin. Chem. vol. 32, p. 817-827.
- Kay, W.B., 1940. "Liquid-Vapor Equilibrium relations in Binary Systems: Ethane - n - Butane system". Industr. Engin. Chem. vol. 32, p. 353-358.
- Kennedy, G.C., 1950a. "Pneumatolysis" and the liquid inclusions method of geologic thermometry". Econ. Geol. vol. 45, p. 533.
- 1950b. "Pressure-volume-temperature relations in water at elevated temperatures and pressures". Amer. Journ. Sci, vol. 248, p. 540-564.
- 1954. "Pressure-volume-temperature relations in CO_2 at elevated temperatures and pressures". Amer. Journ. Sci, vol. 252, p. 225.
- Khitarov, N., 1956a. "The 400° isotherm for the system $\text{H}_2\text{O} - \text{SiO}_2$ at pressures up to 2,000 kg/cm²". Geochemistry no. 1, p. 55-57, translated of Geokhimiya 1956, no. 1.
- Khitarov, N. & Malinin, C., 1956b. "Pressure-temperature-volume relations of the system $\text{H}_2\text{O} - \text{CO}_2$ ". Geochemistry no. 3, p. 248-256, translated of Geokhimiya 1956.
- Khitarov, N.I., 1957. "The chemical properties of solutions arising as a result of the interaction of water with rocks at elevated temperatures and pressures". Geochemistry no. 6, p. 566-578, translated of Geokhimiya 1957, no. 6.
- Khitarov, N.I. et al. 1958b. "Chemical composition of liquid inclusions in iceland spar and genetic problems". Geochemistry no. 3, p. 269-278, translated of Geokhimiya 1958, no. 3.
- Khitarov, N.I. & Malinin, S.D. 1958. "Phase equilibria in the system $\text{H}_2\text{O} - \text{CO}_2$ ". Geochemistry, p. 846-848, translated of Geokhimiya no. 7, p. 678-679.
- Klevtsov, P.V. & Lemlein, G.G., 1959. "Pressure corrections for the homogenization temperatures of aqueous NaCl solutions (in Russian)".
Doklady Akad. Nauk. S.S.R. vol. 128, p. 1250-1253.
- Koning, L.P.G., 1941. "On gersdorffite in the Falconbridge ore deposit, Sudbury District, Ontario, Canada. Proc. Acad. Sci. Amsterdam, vol. 64.
- Konstantinov, M.M. "Scheme of formation of hydrothermal ore-forming solutions". Izvest. Akad. Nauk. S.S.R. Ser. Geol. no. 1, p. 95-98.
- Kortüm, G., 1952. "Die Theorie der Destillation und Extraktion von Flüssigkeiten". Heidelberg, 1952.
- Kuenen, J.P. & Robson, W.G., 1899. Phil. Mag. bd. 48, p. 180, 1899, Zeits. Phys. Chem. bd. 28, p. 342, 1899.
- Kuenen, J.P., 1906. "Theorie der Verdampfung und Verflüssigung von Gemischen". Leipzig.
- Kullerud, G., 1953. "The FeS-ZnS system, a geological thermometer". Norsk. geol. Tidsskr. vol. 32, p. 62-144.
- 1956. "Subsolidus relations in the Fe-Ni-S system. Pentlandite-pyrrhotite". Carnegie Inst. Washington. Ann. Geophys. vol. 55, p. 175.
- Kulp, J.L., 1960. "The geological time scale". 21e Intern. Geol. Congress part 3, p. 18-27.
- Kutina, J., 1957. "The role of replacement in the Origin of cockade

- textures". *Econ. Geol.* vol. 53.
- Lehner, V. & Crawford, W.G., 1913. "A new colorometric method for titanium". *Journ. Amer. Chem. Soc.* vol. 35, p. 138-145.
- Lemlein, G., 1929. "Sekundäre Flüssigkeitseinschlüsse in Mineralien". *Zeits. Krist.*, 71, p. 237-256.
- 1956. "Formation of fluid inclusions in minerals and their use in geological thermometry". *Geochemistry* no. 6, p. 630-642, translated of *Geokhimiya* 1956, no. 6.
- Lemlein, G. & Klevtsov, P.V., 1961. "Relations among the principal thermodynamic parameters in a part of the system $H_2O - NaCl$ ". *Geochemistry* no. 2, p. 148-158, translated of *Geokhimiya* 1961, no. 2.
- Lindgren, 1933. *Amer. Miner.* vol. 18, p. 548.
- Lisitsin, A. & Malinko, S.V., 1961. "Character of mineral-forming solutions according to results of investigation of liquid inclusions in quartz". *Geochemistry* no. 9, p. 867-876, translated of *Geokhimiya* 1961, no. 9.
- Little, W.M., 1955. "A study of inclusions in cassiterite and associated minerals". Ph.D. thesis, Univ. of Toronto.
- Malinin, S., 1959. "The system water-carbon dioxide at high temperatures and pressures". *Geochemistry* no. 3, p. 292-305, translated of *Geokhimiya* 1959, no. 3.
- Maslova, I.N., 1961. "Ultramicrochemical investigations of compositions of the liquid and vapour phases in two phase inclusions from Volynia". *Geochemistry* no. 2, p. 190-196, translated of *Geokhimiya* no. 2.
- Morey, G.W. & Hesselgesser, J.M., 1951. "The solubility of some minerals in superheated steam at high pressures". *Econ. Geol.* vol. 46, p. 821-835.
- Morey, G.W., Fournier, R.D. & Rowe, J.O., 1962. "The solubility of quartz in water in the temperature interval from 25° to 300° C.". *Geochimica et Cosmochimica Acta*. Vol. 26, p. 1029-1043.
- Niggli, P. & Burri, C., 1945. "Die jungen Eruptivgesteine des mediterranen Orogens, I". Zürich.
- Niggli, E., 1956. "Stilpnomelan als gesteinsbildender Mineral in dem Schweizeren Alpen". *Schweiz. Miner. Petr. Mitt.* bd. 36, p. 511-514.
- Novak, F., 1962. "Kriterien bei der Beurteilung alpidischer Regenerationsprozesse in hydrothermalen Lagerstätten der Gemeriden". *Geologické Práce - band 61*, p. 113-127.
- 1962. "Processus de régénération métallogénique d'âge alpin dans les monts métallifères du Spis et du Gemer". *Trav. Lab. Geol.* tome 38, p. 219-230.
- Orcel, J., 1942. "La Coronadite et le minerai qui la renferme dans les gites de manganese de l'Imini". *Bull. Soc. France. Miner.* tome 65, p. 73-125.
- Palache, C., Berman, H. & Frondel, C., 1944. "Dana's system of mineralogy". vol. 1, Wiley, New York.
- Parker, R.L. & Niggli, P., 1940. "Die Mineralien der Schweizer Alpen". Basel.
- Peacock, M.A. & Berry, L.G., 1937. "Studies of mineral sulphosalts: XIII. Polybasite and paracelite". *Miner. Mag.* vol. 28, p. 1-13.
- Pollard, F.H. & McOmie, 1953. "Chromatographic Methods of anorganic analyses". *Academie Press* New York.
- Ramdohr, P. & Ödman, O., 1939. "Falkmanit, ein neues Bleispieszglanzlerz und sein Vorkommen". *Neues Jb. Miner. Beil.* bd. 75, p. 315-350.
- Ramdohr, P., 1953. "Mineralbestand, Strukturen und Genesis der Rammelsberg Lagerstätte". *Geol. Jahrb.* bd. 67, p. 115-242.
- 1960. "Die Erzminerale und Ihre Verwachsungen". Berlin.
- Roedder, E., 1960. "Fluid inclusions as samples of the ore-forming fluids". *XXI Internat. Geol. Congr., Proc. of Sec. 16- Genetic problems of ores*, p. 218-229.
- 1962. "Studies of fluid inclusions I: low temperature application of a dual-purpose freezing and heating stage". *Econ. Geol.* Vol. 57, p. 1045-1061.
- Rosenberg, P.E., 1959. "Subsolidus relations on the join $CaMg(CO_3)_2 - CaFe(CO_3)_2$ of the system $CaCO_3 - MgCO_3 - FeCO_3$ ". *Bull. Geol. Soc. Amer.* vol. 70, p. 1664.
- Sage, B.H. et al., 1940. "Phase Equilibria in Hydrocarbon systems: Methane - n - Butane system". *Industr. Engin. Chem.* vol. 32, p. 1263-1277.
- 1942. "Phase Equilibria in Hydrocarbon Systems: Methane - n - Pentane system". *Industr. Engin. Chem.* vol. 34, p. 1108-1117.
- Sander, W., 1912. "Die Löslichkeit der Kohlensäure in Wasser und einigen andern Lösungsmitteln unter höhern Drucken". *Zeits. Phys. Chem.* bd. 78, p. 513-549.
- Savul, M.A. & Pomirleanu, V.V., 1958. "The statistical method of determining the homogenization temperature of liquid inclusions". *Geochemistry* no. 3, blz. 259-268, translated of *Geokhimiya* 1958, no. 3.
- Schneiderhöhn, H., 1941. "Lehrbuch der Erzlagerstättenkunde". Jena.
- 1952. "Genetische Lagerstättengliederung auf geotektonischer Grundlage". *Neues Jahrb. Miner. Monatshefte* 2, 3, p. 47-63, 65-89.
- 1953. "Fortschritte in der Erkenntnis sekundär hydrothermalen und regenerierter Lagerstätten". *Neues Jahrb. Miner. Monatshefte* 9, 10, p. 223 to 237.
- Schroll, E., 1955. "Über das Vorkommen einiger Spurenelemente in Blei - Zink - Erzen der ostalpinen Metallprovinz". *Tscherm. Miner. Petr. Mitt.* bd. 5, p. 183-208.
- 1956. "Bemerkungen zur "alpinen Metallogene" der Kalkalpinen Blei - Zink - Lagerstätten". *Tscherm. Miner. Petr. Mitt.* 5, no. 1, 2, p. 96-98.
- Schwartz, G.M., 1931. "Intergrowths of bornite and chalcopyrite". *Econ. Geology* vol. 20, p. 186-201.
- Schwarzenbach, 1954. "Die complexometrische Titration".
- Scott, H.S., 1948. "The decrepitation method applied to minerals with fluid inclusions". *Econ. Geol.* vol. 43, p. 637-654.
- Shapiro, L. & Brannock, W.W., 1956. "Rapid analysis of silicate rocks". *U.S. Geol. Survey Bull.* 1036-C, p. 19-55.
- Skinner, B., 1959. "Revision of Kullerud thermometer". *Econ. Geol.* vol. 54, p. 1040-1046.
- Smith, F.G., 1951. "Determination of the temperature and pressure of formation of minerals by the decrepitation method". *Econ. Geol.*, 46, p. 112.
- Smith, F.G. & Little, W.M., 1959. "Filling temperatures of H_2O-CO_2 fluid inclusions and their significance in geothermometry". *Canad. Miner.* Vol. 6, 1959, p. 380-390.
- Smyth, J.A. & Dunham, K., 1947. "Ankerites and chalybites from the northern Pennine orefield". *Miner. Mag.* vol. 28, p. 53.
- Sobelman, 1962. "Données sur les solutions post magmatiques et le problème de la température et pression en thermometrie metallogen." *Soviet Geol.* no. 1, p. 93-103.
- Sorby, H.C., 1858. "On the microscopical structure of crystals, indicating the origin of minerals and rocks". *Quart. Jour. Geol. Soc.*, 14, p. 453-500.
- Sugaki, A. & Yamae, N., 1950. "Thermal study of copper ores from the Akayama Mine, Japan. *Jour. Jap. Assoc. Miner.* vol. 34, p. 173-178.
- Tschermak, G., 1891. "Die Chloritgruppe". *Sitzber. Akad. Wiss. Wien*, vol. 100, p. 29.
- Van der Veen, R.W., 1925. "Mineragraphy and ore deposition". Den Haag.
- Wahler, W., 1956. "Über die in Kristallen eingeschlossenen Flüssigkeiten und Gase". *Geochimica et Cosmochimica acta.* vol. 9, p. 105-136.
- Wiebe, R. & Gaddy, V.L., 1939. "Solubility in water of carbon dioxide at 500, 750 and 1000° C and pressure to 700 atm. *Journ. Amer. Chem. Soc.* vol. 61, p. 315-318.
- Wolfson, F.I., 1960. "Die Strukturen der endogenen Erzlagerstätten". Berlin, 1960.
- Wretblad, P.E., 1941. "Die Allemontite". *Geol. Fören. Förh.* bd. 63, p. 19-48.
- Yermakov, N.P., 1949. "Inclusions primo-secondaires dans les minéraux". *Mineral. Sbornik Geol. Soc. L'vov.* no. 3, p. 23-27.
- 1950. "Studies of mineral-forming solutions (in Russian)". *Univ. of Kharkov*, 460 p.
- Yermakov, N.P. & Kalyuzhnyi, 1957. "The possibility of determining true temperatures of mineral-forming solutions". *Translated in international Geology Review* vol. 3, 1961, p. 706.
- Yermakov, N.P., 1957b. "Importance of inclusions in minerals to the theory of ore genesis and study of the mineral forming medium". *Translated in international Geology Review*, vol. 3, 1961, p. 575.

SELECTED REFERENCES

ON THE GEOLOGY AND ORE DEPOSITS OF THE BELLEDONNE

- Allix, A., 1917. "Vizille et le bassin inférieur de la Romanche". Rev. Geog. Alpine, tome 5, p. 1-199.
- Barbier, V., 1875. "La Savoie industrielle". Acad. Sci. Bel. Lettr. Savoie, 3e série, tome II et III.
- 1878. "La Savoie minière et thermale". Chambéry 1878.
- Bellaïr, P., 1948. "Pétrographie et tectonique des massifs centraux dauphinois". Thèse, Paris 1948.
- Bellièvre, J., 1958. "Contribution à l'étude pétrogenétique des schistes cristallins du massif des Aiguilles-Rouges (Haute-Savoie)". Ann. Soc. Géol. Belgique, tome 81, p. 1-198.
- Berthier, 1819. "Analyse du nickel arsenical et du nickel arséniaté d'Allemont (Isère)". Ann. Mines, tome 4, p. 467-482.
- Berthier, P., 1820. "Sur les minerais de fer appelés mines douces". Ann. Mines, tome 9.
- Berthier, A.H., 1828. Ann. Mines, tome 3, p. 32.
- 1839. Ann. Mines, tome 8, p. 494.
- Billaz, 1907. "En Alleverd". Paris 1907.
- Blanchard, R., 1941. "Les Alpes occidentales". Grenoble 1941.
- Bordeaux, A., 1925. "La Géologie et les Mines de la Savoie et des Régions avoisinantes". Mines et Carrières, Paris 1925.
- Bordet, Cl., 1957. "Recherches géologiques sur la partie septentrionale du Massif de Belledonne". Thèse, Paris.
- Borel, 1889. "Notice historique sur les mines de Savoie". Recueil de mémoires de l'Académie de la Val-d'Isère, série des Mémoires, 4e vol., 4e livraison, p. 297.
- Bouchayer, A., 1927. "Les Chartreux, Maîtres de Forges". Grenoble.
- Bourgin, H., 1920. "L'industrie sidérurgique en France au début de la Révolution (Isère et Savoie)". Paris, Impr. Nat.
- Brückner, W., 1941. "Über die Entstehung der Rauhacken und Zellendolomite". Ecol. Geol. Helvetiae, vol. 34, p. 117-134.
- Brunier, L., 1853. "Exploitation des mines de fer de Saint-Georges-d'Hurthières en Maurienne". Turin.
- Buffaut, P., 1936. "Minerais et exploitations minières du Dauphiné". Revue General Sci. 1936.
- Bunge, E.M., 1931. "Etude géologique de la zone synclinale de Cevins en Tarentaise (Savoie)". Trav. Lab. Geol. Grenoble, tome 16.
- Caillaux, A., 1870. "Les Mines métalliques de la France". Paris, 55 p.
- Camous, L.V., 1905. "Etude sur le fer spathique du Dauphiné et ses transformations". Assoc. franc. avancement des Sciences.
- Carcel, Ch., 1936. "La Région du Gelon". Rev. Geogr. Alpine, tome 24, p. 261-313.
- Carnot, 1890. "Analyses de minerais de fer d'Alleverd". Ann. Mines, tome 18, p. 5.
- Chabrand, E., 1892. "Essai historique sur les origines de l'exploitation des mines métalliques et de la métallurgie dans les Alpes du Dauphiné". Grenoble, Drevet.
- 1900. "Histoire de la métallurgie du fer et de l'acier en Dauphiné et en Savoie". Biblioth. scient. du Dauphiné, Grenoble, Drevet.
- 1905. "Les anciennes fonderies des Alpes delphino-savoisiennes". Assoc. franc. avancement des Sciences. Congrès de Grenoble, 1905.
- 1906. "Venues métallifères des Alpes delphino-savoisiennes. Essai de synthèse métallogénique". Assoc. franc. avancement des Sciences. Congrès de Lyon.
- 1914. "Coup d'oeil général sur la géographie minière des Alpes dauphinoises". Annuaire de la Société des Touristes du Dauphiné, Grenoble, p. 193-244.
- Choubert, G., 1934. "La serpentine du Tabor (Extrémité sud du Massif de Belledonne, Dauphiné)". Trav. Lab. Géol. Grenoble, tome 18, p. 51-120.
- Collet-Dexcoctils, 1806. "Observations chimiques sur le fer spathique (région d'Alleverd, Vaulnavays)". Journ. des Mines, tome 18, p. 211-230.
- Corsin, P. & Tobi, A., 1954. "Nouvelles données sur l'âge des grès d'Alleverd (Massif de Belledonne)". Compt. rend. Acad. Scienc. tome 259, no. 16, p. 984-986.
- Demaret, L., 1914. "Atlas de géographie économique. Gisement des minerais". Paris.
- Dolomieu, 1795. "Vues générales sur le Dauphiné". Manuscript publié par A. Lacroix. Bull. Soc. Stat. Isère, 4e série, tome 14, 1919.
- Dondey, D., 1960. "Contribution à l'étude de la série crystallophyllienne et de la couverture sédimentaire de la chaîne de Belledonne méridionale (Alpes françaises)". Trav. Lab. Geol. Grenoble, tome 36, p. 285-368.
- Du Bosc, 1815. "Essais faits dans une forge catalane de l'Ariège des minerais de fer du canton d'Alleverd". Journ. des Mines, tome 38, p. 137-159.
- Frenzel, 1875. Neues Jahrbuch. p. 677.
- Gaillard, E., 1924. "Les Alpes du Dauphiné, Les Massifs de Belledonne et des Sept Laux". Dardel, Chambéry.
- 1924. "Les Alpes de Savoie". Dardel, Chambéry.
- Gignoux, M. & Moret, L., 1952. "Géologie dauphinoise". Paris, Masson.
- Graff, 1868. "Notice sur la mine d'argent des Chalanches". Bull. Soc. Sci. indust. Lyon, 1868.
- Gras, Sc., 1851. "Mine de Mercure trouvée près de la Mure". Bull. Soc. Stat. Isère, 2e série, tome 8, p. 562-564.
- Grillet, 1807. "Dictionnaire du département du Mont-Blanc et du Léman". Chambéry, Putrod.
- Groth, P., 1885. "Die Minerallagerstätten der Dauphiné". Sitzungsber. der math. phys. Klasse d. Akad. d. Wissensch.
- Guettard, 1779. "Mémoires sur la minéralogie du Dauphiné". Paris imp. de Clausier, 2 vol. in 4.
- Gueymard, E., 1839a. "Analyse des minerais de fer d'Alleverd". Ann. Mines. 3e série, tome 15, p. 598-607.
- 1839b. "Sur les gîtes d'argent de la montagne des Chalanches". Bull. Soc. Stat. Isère, 1e série, p. 27.
- 1840. "Notice sur le grillage des minerais de fer dans le département de l'Isère". Ann. Mines. 3e série, tome 18, p. 707-716.
- 1844. "Statistique minéralogique, géologique, et métallurgique du département de l'Isère". Statistique générale du département de l'Isère, Grenoble, Allier.
- 1855. "Note sur des gîtes de nickel dans le département de l'Isère". Compt. Rendu Acad. Sci., tome 40, p. 984.
- 1857. "Gisements métalliques de la Savoie et du Dauphiné". Congr. scient. de France. Grenoble, p. 425-432.
- Haudour, J. & Sarrot-Reynauld, J., 1956. "Le Bassin houiller de la Mure, ses minéraux". Trav. Lab. Geol. Grenoble, tome 32, p. 15-20.
- Héricart de Thury, L., 1806. "Description minéralogique du département de l'Isère. Montagne et mines d'Argent des Chalanches". Journal des Mines, tome 20, p. 41.
- Hintze, C., 1904-1912. "Handbuch der Mineralogie". Leipzig.
- Hollande, D., 1911. "Quelques remarques au sujet de minerais trouvées en Savoie". Bull. Soc. hist. nat. de Savoie, tome 16, p. 60-80.
- Hörnès, 1846. Neues Jahrbuch. p. 781.
- Huttenlocher, H.Th., 1936. "Die Erzlagerstättenzonen der West Alpen". Schweiz. Min. Petr. Mitt. bd. 14, p. 22-60.
- Janse, A.J.A., 1956. Unpublished report on the petrology of the Prabert - Pas de la Coche Area (Belledonne, France). Leiden.
- Kalsbeek & Koning & den Tex, 1961. "Complementary wrench faults and related structures in the crystalline rocks of the Belledonne Massif (French Alps)". Geologie & Mijnbouw, vol. 40, p. 241-249.
- Kalsbeek, F., 1962. "Petrology and structural geology of the Berlanche - Valloire area. Belledonne Massif, France". Thesis, Leiden.
- Küss, H., 1885. "L'industrie minière dans le Dauphiné en 1885". Grenoble.
- Lacroix, A., 1893. "Minéralogie de la France". Paris 1893-1913.
- de Launay, L., 1895. "Les gîtes métallifères des Alpes françaises". Le Monde moderne, Paris, p. 435-442.
- 1913. "Traité de métallogénie. Gîtes minéraux et métallifères". Paris, 1913.
- Lelivec, 1805. "Mines de fer et forges du département du Mont Blanc". Journ. Mines, tome 17, p. 123-164.
- 1806. "Statistique du département du Mont Blanc". Journ. Mines, tome 19-20, p. 460.

- Lesage, 1777. "Elements de Minéralogie". p. 71.
- Lory, Ch., 1861. "Description géologique du Dauphiné". Bull. Soc. Stat. Isère, tome 6, p. 1-260. Grenoble, Maisonville.
- Lory, P., 1925. "Sur la tectonique alpine de la chaîne de Belledonne au Sud d'Albertville". Compt. Rendu Soc. géol. France, p. 23-25.
- 1944. "Révision des feuilles de Dié et de Vizille au 80.000^e". Bull. Serv. Cart. Geol. France no. 216, tome 45.
- Maron, P., 1956. Unpublished report on the petrology of the Allemont area, Belledonne (France). Leiden.
- Michel, R. & Berthet, P., 1958. "Les formations cristallophylliennes de la chaîne de Belledonne dans la vallée de la Romanche (Isère)". Compt. Rendu Acad. Sci. Paris, tome 246, p. 1888-1890.
- Michel, R. & Debelmas, J., 1961. "Silicifications par altération climatique dans les séries alpines". Trav. Lab. Geol. Grenoble, tome 37, p. 7-15.
- Monnet, P., 1927. "Le pays d'Allevard". Rev. Geogr. alpine, tome 15.
- Moret, L., 1925. "Enquête critique sur les ressources minérales de la Province de Savoie, précédée d'une esquisse géologique". Trav. Lab. Geol. tome 14, p. 1-201.
- 1952. "Les synclinaux fermés et inapparents des massifs cristallins externes des Alpes occidentales". Trav. Lab. Geol. Grenoble, tome 29, p. 97-100.
- Niggli, E., 1953. "Zur Stereometrie und Entstehung der Aplit - Granit - und Pegmatitgänge im Gebiete von Sept Laux (Belledonne Massiv s.l.)". Leidse Geol. Med. deel 17, p. 215-236.
- Nicolet, S.E., 1931. "Les gisements filoniens de sidérose d'Allevard (Dauphiné)". Thesis, Genève.
- Pilot, J.J.A., 1887. "Allevard et son mandement". Grenoble, 1887.
- Rammelsberg, 1844. "Allemontite". Poggendorf Ann. bd. 62, p. 139.
- Revil, J., 1916. "Les richesses industrielles et minérales de la Savoie". Bull. Soc. hist. nat. de Savoie, 2e série, tome 18, p. 132-162.
- Romé de l'Isle, J.B.L., 1783. "Cristallographie". Paris.
- Sarrot-Reynauld et al., 1957. "Sur un nouveau faciès de la barytine dans les minéralisations du Dôme de La Mure (Isère)". Trav. Lab. Geol. Grenoble, tome 33, p. 123-124.
- Sarrot-Reynauld, J., 1957. "Les minerais métalliques et les sources minérales de la région de la Mure". Trav. Lab. Geol. Grenoble, tome 33, p. 135.
- 1958. "Le socle cristallophyllien du Dôme de la Mure. Age et caractères du métamorphisme". Compt. Rendu Acad. Sci. tome 246, p. 2008-2011.
- Sarrot-Reynauld, J. & Debelmas, J., 1960. "Le Réseau de failles du Massif du Taillefer". Trav. Lab. Geol. Grenoble, tome 36, p. 51-59.
- de Saussure, H.B., 1779. "Voyages dans les Alpes". Neuchâtel, 1779-1796.
- Schreiber, J.G., 1784. "Observations sur la Montagne des Chalanches (près d'Allemont, Isère)". Journ. de Phys. mai 1784. Bull. Soc. Stat. Isère, tome 1, p. 114-123.
- 1786. "Espèces de mines qui se trouvent dans les filons de la Montagne des Chalanches". Journ. de Phys. p. 143-148.
- 1788. "Sur une mine d'argent" (Allemont). Journ. de Phys. p. 368-370.
- 1798. "Notice sur la découverte du Mercure coulant dans la mine d'Allemont (Isère) et sur la mine de mercure de Saint-Arey (Isère)". Journ. de Phys., tome 9.
- Sclafert, T., 1926b. "Le Haut Dauphiné en Moyen Age". Paris 1926.
- 1926a. "L'Industrie de fer dans la région d'Allevard en Moyen Age". Rev. Geogr. Alpine, tome 14, p. 239-355.
- Tenot, S., 1919. "Le Massif de Belledonne". Rev. Geogr. Alpine, tome 7, p. 601-689.
- Termier, P., 1897. "Sur la bournotite de Peychagnard (Isère)". Bull. Soc. franc. Miner. tome 20, p. 101-110.
- den Tex, 1950. "Les roches basiques et ultrabasiqes des Lacs Robert et le Trias de Chamrousse". Leidse Geol. Med. deel 15, p. 1-204.
- Tirloir, A., 1878. "Gîtes métallifères du Dauphiné". Bull. Soc. d'etudes des Sci. nat. de Nîmes, 5e année.
- Tobi, A.C., 1958. "Volcanisme occulte dans les grès d'Allevard (Permien) et dans le Houiller du Massif de Belledonne (Isère)". Compt. Rendu Acad. Sci. France, tome 246, p. 3654-3656.

- Tobi, A.C., 1959. "Petrographical and geological investigations in the Merdaret - Lac Crop region (Belledonne Massif - France)". Leidse Geol. Med. deel 24, p. 181-283.
- Touwen, N.A.L., 1957. Unpublished report on the petrology of the Vallée de St. Hugon and le Grand Collet area, Belledonne (France). Leiden.
- Verneihl (de), 1807. "Statistique du département du Mont Blanc". Paris.
- Vesignie, 1951. "Présentation d'échantillon". Bull. Soc. fr. Mineral. no. 1, p. 42.
- Wart, v.d., 1959. Unpublished report on the petrology of the River d'Allemont area, Belledonne (France). Leiden.

LIST OF ORE OCCURRENCES
















Name	Number	Position	Maps
André (St.)	- 69-	346.4 ; 892.8	Allevard
Allevard	- 42-	349.6 ; 893.2	Allevard
Alloues (les)	- 9-	317.6 ; 874.2	Vizille
Argentine	-112-	363.2 ; 912.6	Aiguebelle
Beauregard	- 31-	327.5 ; 888.8	Allemont
Bonvillard	-108-	373 ; 913	Bonvillard
Cabot	- 67-	346.9 ; 893.8	Allevard
Chalanches	- 23-	321.7 ; 887.5	Allemont
Chamrousse	- 27-	320.1 ; 880.8	Vizille
Chaume (la)	- 73-	347.3 ; 893.0	Allevard
Charles (St.)	- 2-	314.3 ; 872.1	Vizille
Charles (St.)	- 34-	330.4 ; 889.5	Allemont and Fond de France
Chevrette (la)	- 91-	347.7 ; 897.5	Allevard and Aiguebelle
Clavette	- 52-	350.7 ; 894.7	Allevard
Col de Sifflet	- 35-	330.3 ; 889.3	Allemont and Fond de France
Combe Noire	- 64-	347.6 ; 893.7	Allevard
Coudre (le)	- 84-	340.9 ; 890.5	Fond de France
Crop (Lac du)	- 37-	328.3 ; 885.8	Allemont
Cuchet	- 58-	348.6 ; 893.1	Allevard
De la Met	- 51-	350.5 ; 894.4	Allevard
Doua (le)	- 95-	354.6 ; 901.5	Aiguebelle
Du Rocher	- 62-	348.1 ; 893.4	Allevard
Envers	- 44-	351.3 ; 894.8	Allevard
Espérance	- 59-	348.4 ; 893.4	Allevard
Essarts (les)	- 38-	337.5 ; 891.7	Fond de France
Esserts-Blay	-111-	377.5 ; 918.4	Bonvillard
Etellier	- 57-	348.6 ; 893.5	Allevard
Fare (la)	- 25-	322 ; 866	Allemont
Fayolle (la)	- 21-	305 ; 871.5	Geological map
Feuillette (la)	- 76-	344.2 ; 890.4	Allevard
Fond de France	- 90-	337.5 ; 894	Fond de France
Fortune (la)	- 68-	346.7 ; 893.4	Allevard
Fosse Guerre	-101-	360.5 ; 903.2	Aiguebelle
Fruithiers (les)	- 97-	359.4 ; 901.3	Aiguebelle
Gangrette	- 65-	347.4 ; 893.5	Allevard
Genivelle	- 78-	342.6 ; 891.0	Allevard
Georges des Hurt. (St.)	-105-	364 ; 907	Aiguebelle
Girodet	- 81-	342.3 ; 892.2	Allevard
Gorges (les)	-107-	359.1 ; 906.2	Aiguebelle
Grande Bois	- 29-	324.2 ; 890.3	Allemont
Grande Chambre	- 16-	312.5 ; 873.2	Vizille
Grande Combe	- 6-	314.7 ; 872.5	Vizille
Grande Roche	- 36-	330.5 ; 893	Fond de France
Grande Taillée	- 49-	351.0 ; 894.3	Allevard
Gros Chêne	- 48-	351.0 ; 894.0	Allevard
Halles (les)	- 9-	317.6 ; 874.2	Vizille
Hugon (St.)	- 92-	351.4 ; 899.8	Allevard and Aiguebelle
Jacques (St.)	- 47-	351.4 ; 894.3	Allevard
Jasse (Lac de la)	- 87-	333.8 ; 889.3	Fond de France
Joseph (st.)	- 45-	351.3 ; 894.9	Allevard
Julie (St.)	- 5-	near Gd. Fosse	Vizille
Lac Crop	- 37-	328.3 ; 885.8	Allemont
Lac de la Jasse	- 87-	333.8 ; 889.3	Fond de France
Longerolle	- 20-	309.5 ; 871.9	Geological map
Malatrait	- 53-	350.6 ; 895.1	Allevard
Malpourchié	- 32-	327.5 ; 888.9	Allemont
Malrocher	- 98-	357.1 ; 902.1	Aiguebelle
Maramaille	- 61-	347.8 ; 893.3	Allevard
Merdaret	- 86-	338 ; 889	Fond de France
Merle (le)	- 80-	342.0 ; 890.2	Allevard
Met (de la)	- 51-	350.5 ; 894.4	Allevard
Molliet	- 88-	355.9 ; 897.7	Aiguebelle
Montchaffrey	- 11-	317.3 ; 874.3	Vizille

Name	Number	Position	Maps
Montgilbert	-106-	364 ; 907	Aiguebelle
Mont Jean	- 7-	315.1 ; 872.9	Vizille
Mouches (les)	-104-	363.6 ; 906.3	Aiguebelle
Oliver	- 10-	317.5 ; 874.4	Vizille
Panissière	- 56-	349.0 ; 893.6	Allevard
Parc (le)	- 12-	313.1 ; 871.1	Vizille
Paturel	- 79-	342.7 ; 891.0	Allevard
Paul (St.)	-110-	374.5 ; 919.5	Bonvillard
Perrelle	-102-	362.2 ; 804.0	Aiguebelle
Perrière	- 96-	351.9 ; 901.3	Aiguebelle
Peyrère (Peyreire)	- 20-	309.5 ; 871.9	Geological map
Pierre de Mésage (St.)	- 15-	near the village	
Pierre Herse	- 85-	337.4 ; 889.2	Fond de France
Pierre Plâte	- 1-	314.4 ; 871.9	Vizille
Pierre Rousse	- 14-	312.1 ; 871.7	Vizille
Pilliard	- 66-	347.3 ; 893.5	Allevard
Pioulaz	- 77-	343.7 ; 890.4	Allevard
Plan de Chêvre	- 63-	348.2 ; 893.8	Allevard
Pomine	- 70-	346.3 ; 892.8	Allevard
Pont Rouge	- 24-	320.7 ; 888.2	Allemont
Prévieux	- 99-	358.0 ; 901.6	Aiguebelle
Rodrin	- 94-	355.8 ; 899.9	Aiguebelle
Rafour	- 43-	351.4 ; 894.8	Allevard
Ravoire	- 54-	349.8 ; 894.2	Allevard
Reagout	- 46-	351.3 ; 895.0	Allevard
Remout	- 93-	355.4 ; 900.5	Aiguebelle
Richesse	-103-	359.2 ; 903.7	Aiguebelle
Rochefort	- 74-	345.3 ; 892.7	Allevard
Roche Moutas	- 26-	322.6 ; 886.8	Allemont
Roche Noire	- 30-	327.0 ; 888.2	Allemont
Rocher (du)	- 62-	348.1 ; 893.4	Allevard
Rossignon	- 60-	348.1 ; 893.2	Allevard
Ruines (les)	- 18-	312.3 ; 873.7	Vizille
Ruisson (Pont Rouge)	- 24-	320.7 ; 888.2	Allemont
Sapey (le)	- 17-	310.5 ; 873.9	Vizille
Sophie (St.)	- 55-	349.3 ; 893.4	Allevard
St. André	- 69-	346.4 ; 892.8	Allevard
St. Charles	- 2-	314.3 ; 872.1	Vizille
St. Charles	- 34-	330.4 ; 889.5	Allemont and Fond de France
St. Georges des Hurt.	-105-	364 ; 907	Aiguebelle
St. Hugon	- 92-	351.4 ; 899.8	Aiguebelle
St. Jacques	- 47-	351.4 ; 894.3	Allevard
St. Joseph	- 45-	351.3 ; 894.9	Allevard
St. Paul	-110-	374.5 ; 919.5	Bonvillard
St. Pierre de Mésage	- 15-	near the village	
St. Sophie	- 55-	349.3 ; 893.4	Allevard
Taillat de l'Oule	- 98-	357.1 ; 902.1	Aiguebelle
Taillat maillat	- 72-	346.9 ; 892.7	Allevard
Taillat rives	- 71-	347.2 ; 892.8	Allevard
Tavernes	- 75-	344.7 ; 892.5	Allevard
Tilleray	- 50-	350.6 ; 893.7	Allevard
Trois Laux	- 33-	329.1 ; 888.5	Allemont and Fond de France
Vaudaine	- 28-	321.8 ; 882.9	Allemont
Vaujalaz	- 83-	338.8 ; 891.9	Fond de France
Vent (le)	- 8-	315.3 ; 873.1	Vizille
Vernay	- 13-	313.3 ; 871.7	Vizille
Violettes (les)	- 82-	340 ; 891	Fond de France
Voudène	- 28-	321.8 ; 882.9	Allemont



BELLEDONNE RANGE

based on the 1:80,000 geological maps of:
 Albertville, St.Jean de Maurienne, Vizille and the 1:50,000 map
 of Bourg St. Maurice; corrected after P. Bordet, Cl. Bordet, A.C. Tobi,
 F. Kalsbeek and personal observations (P.Ypma)

- | | | | |
|---|--|---|--|
|  JURASSIC | UNDIFFERENTIATED, MAINLY OF ALLOCHTHONOUS POSITION (COLLINES LIASSIQUES) |  GRANODIORITES | |
|  LIASSIC | SHALES AND LIMESTONES OF PAR-AUTOCHTHONOUS SEDIMENTARY COVER |  | "RAMEAU EXTERNE"-SCHISTS, MAINLY ALBITE-SERICITE-CHLORITE SCHISTS |
|  TRIASSIC | CAVERNOUS LIMESTONES, SPILITES AND DOLOMITES |  | "RAMEAU INTERNE"-GNEISSES AND SCHISTS, MAINLY OF MESO-METAMORPHIC GRADE |
|  PERMIAN | CONGLOMERATES AND SANDSTONES (GRÈS D'ALLEVARD) |  | AMPHIBOLITES AND HORNBLÉNDE-PLAGIOCLASE-GNEISSES |
|  UP. CARB. | CONGLOMERATES, RHYOLITES, BLACK SHALES AND COAL SEAMS |  | ULTRABASIC ROCKS OF TABOR AND LACS ROBERT |
| | |  | SYNCLINAL MEDIAN |
| | |  | FAULT |
| | |  | ORE-DEPOSITS, SIGNATURE DENOTING STRIKE AND LOCALITY NUMBER |
| | |  | LAMBERT'S KILOMETRIC SQUARE GRID, DIVIDING THE REGION INTO SQUARES OF 25 KM ² |
| | |  | MERIDIANS (PARIS 0°) AND DEGREES OF LATITUDE |

